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Development of Standard Procedures for Evaluating Oxygen Transfer Devices

American Society of Civil Engineers, New York

Prepared for

Municipal Environmental Research Lab.
Cincinnati, OH

Oct 83

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In an effort to obtain consensus standards for the evaluation of aeration devices in both clean and dirty water, the American Society of Civil Engineers (ASCE) established a Subcommittee on Oxygen Transfer Standards in January 1977. The objectives of the Subcommittee were to review and critically evaluate the state-of-the-art of oxygen transfer testing, evaluate and critically review existing standards and identify critical areas of disagreement and uncertainty, develop documentation for recommendations for interim standards and recommended verification methodology, and prepare these standards and submit them for ASCE consensus evaluation. This report presents the outcome of this review process and provides recommended procedures for testing of oxygen transfer devices in both clean and dirty water.

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Development of Standard Procedures for Evaluating Oxygen Transfer Devices

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October 1983

DEVELOPMENT OF STANDARD PROCEDURES FOR EVALUATING OXYGEN TRANSFER DEVICES

by

American Society of Civil Engineers
Oxygen Transfer Standards Subcommittee
William C. Boyle, Chairman

Cooperative Research Agreement No. CR805868

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DISCLAIMER

Although the information described in this report has been funded in part by the U.S. Environmental Protection Agency through Cooperative Research Agreement No. CR805868 to the American Society of Civil Engineers, it has not been subjected to the Agency's required peer and administrative reviews and, therefore, does not necessarily reflect the views of the Agency and no official endorsement should be inferred. Mention of trade names or commercial products does not constitute endorsement or recommendation for use.

FOREWORD

The U.S. Environmental Protection Agency was created because of increasing public and government concern about the dangers of pollution to the health and welfare of the American people. Noxious air, foul water, and spoiled land are tragic testimonies to the deterioration of our natural environment. The complexity of that environment and the interplay of its components require a concentrated and integrated attack on the problem.

Research and development is that necessary first step in problem solution; it involves defining the problem, measuring its impact, and searching for solutions. The Municipal Environmental Research Laboratory develops new and improved technology and systems to prevent, treat, and manage wastewater and solid and hazardous waste pollutant discharges from municipal and community sources; to preserve and treat public drinking water supplies; and to minimize the adverse economic, social, health, and aesthetic effects of pollution. This publication is one of the products of that research and provides a most vital communications link between the researcher and the user community.

This report presents a critical review of the state-of-the-art on the testing and evaluation of oxygen transfer devices. Based on this review, the report develops recommendations for interim standards for testing and evaluating aeration equipment in both clean and dirty water.

Francis T. Mayo, Director
Municipal Environmental Research
Laboratory

ABSTRACT

In an effort to obtain consensus standards for the evaluation of aeration devices in both clean and dirty water, the American Society of Civil Engineers (ASCE) established a Subcommittee on Oxygen Transfer Standards in January 1977. The objectives of the Subcommittee were to

1. review and critically evaluate the state-of-the-art of oxygen transfer testing,
2. evaluate and critically review existing standards and identify critical areas of disagreement and uncertainty,
3. develop documentation for recommendations for interim standards and recommended verification methodology, and
4. prepare these standards and submit them for ASCE consensus evaluation.

This report presents the outcome of this review process and provides recommended procedures for testing of oxygen transfer devices in both clean and dirty water. It is prepared as seven interdependent reports including

1. modelling and data interpretation,
2. unsteady state clean water tests,
3. effects of wastewater characteristics and temperature on oxygen transfer,
4. oxygen transfer measurements in respiring systems,
5. geometry and mixing considerations,
6. gas flow measurement, and
7. power measurement.

This report was submitted in fulfillment of Cooperative Research Agreement No. CR805868 by the American Society of Civil Engineers under the partial sponsorship of the U.S. Environmental Protection Agency and covers the period from March 1978 to December 1980.

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SYMBOLS AND NOMENCLATURE

DIMENSIONS

m = mass
L = length
t = time
f = force
T = temperature

STANDARD CONDITIONS FOR REPORTING GAS VOLUME, FLOW RATE, AND DENSITY VALUES

1.00 atm.
20°C
0.0 percent relative humidity

STANDARD CONDITIONS FOR DISSOLVED OXYGEN SATURATION CONCENTRATION

1.00 atm. total pressure at surface
20°C
100 percent relative humidity in gas (mole function of oxygen in gas must be specified)

SYMBOLS

A = activity of dissolved oxygen
a = area of electrode
b = membrane thickness
BHP = brake horsepower of prime mover
C = dissolved oxygen concentration in the liquid phase

Superscripts Used with C

*	denotes an effective average equilibrium (saturation) value corresponding to a given p_O, T, and volume
^	denotes a localized point value (unless identified by this symbol, values of C are assumed to be averaged over a region of volume)

Subscripts Used with C

∞	denotes value attained at infinite time in an unsteady state test
A	denotes value in flow entering the aeration zone
AB	denotes effective value in the aeration zone

SYMBOLS AND NOMENCLATURE (continued)

B	denotes value in flow leaving the aeration zone
b	denotes book value
f	denotes dirty water field conditions
o	denotes value at t = 0, estimated from the model
R	denotes steady state value at a biological uptake rate of R
r	denotes value in the recycle sludge flow, Q_r
s	denotes surface saturation value at 1.00 atm. total pressure and 100 percent relative humidity
T	denotes value at a given temperature, T
TP	denotes value in tap water
ww	denotes value in wastewater
20	denotes value at 20°C

C'_o = dissolved oxygen in the influent flow, Q'

C_p = specific heat at constant pressure

C_v = specific heat at constant volume

CV = coefficient of variation

d = actual internal pipe diameter

d_e = effective saturation depth at infinite time

d_o = orifice bore diameter

E = voltage

e_b = blower efficiency

e_{bs} = standard blower efficiency

e_d = driver efficiency

e_{ds} = standard drive efficiency

e_g = gear box efficiency

e_m = motor efficiency

e_{ms} = standard motor efficiency

e_{poly} = polytropic efficiency of the blower

F = exit gas depletion factor under operating conditions

$\mathcal{F}$ = Faraday = 9.649×10^4 Coulombs/mole

F_a = orifice area correction factor

F_m = manometer correction factor

F_o = exit gas depletion factor at zero DO

F_{pc} = super-compressibility correction factor

F_{pe} = pipe expansion correction factor

F_{vc} = vena contract correction factor

SYMBOLS AND NOMENCLATURE (continued)

F_{wv} = relative humidity correction factor
G = dry gas specific gravity
$\overline{G}$ = sheer modulus of elasticity
G_{df} = specific gravity of the manometer displacing fluid
G_E = mass rate of exit gas
G_F = mass rate of feed gas
G_i = mass rate of inerts in air including nitrogen, argon, and trace elements
G_w = water vapor specific gravity
H = static head
$\overline{H}$ = Henry's Law Constant
h = differential pressure
h_L = diffuser headloss corrected to 68°F
i = current
K = $(k - 1)/k$
k = ratio of specific heats C_p/C_v
K_La^* = true volumetric mass transfer coefficient in clean water adjusted for gas-side oxygen depletion
K_La = apparent volumetric mass transfer coefficient in clean water (not adjusted for gas-side oxygen depletion)

Superscript Used with K_La and K_La^*

^ denotes a localized point value (unless identified by this symbol, values of K_La are to be interpreted as average values over a given volume)

Subscripts Used with K_La and K_La^*

a	denotes value applicable to aeration zone volume
f	denotes value applicable to dirty water field conditions
T	denotes value at a given temperature, T
TP + S	denotes value applicable to tap water with a surfactant added
ww	denotes value applicable to wastewater
20	denotes value at 20°C

M = molecular weight
$\overline{M}$ = test basin water weight
M_a = molecular weight of air
M_i = molecular weight of inerts

SYMBOLS AND NOMENCLATURE (continued)

M_o = molecular weight of oxygen
$MR_{o/i}$ = mole ratio of oxygen in reference air to inerts
$MR_{og/i}$ = mole ratio of oxygen in off-gas air to inerts
N = shaft speed
$\overline{N}$ = concentration of ammonia nitrogen
n = number of moles
n_e = number of electrons transferred in cell reaction
OTE = oxygen transfer efficiency
OTR = oxygen transfer rate
OTR_f = OTR in a dirty water respiring system
P = power
P^* = measured power value
P_m = permeability coefficient
PF = power factor
PHP = prime mover horsepower
p = pressure

Subscripts Used with p

a	denotes ambient pressure
b	denotes base pressure
bw	denotes vapor pressure of water at base conditions
f	denotes flowing gas pressure
o	denotes partial pressure of oxygen
oi	denotes partial pressure of oxygen in the gas phase in the inlet
or	denotes partial pressure of oxygen in the gas phase in the reactor
s	denotes standard pressure of 1 atm.
T	denotes value at a given temperature, T
v	denotes vapor pressure of water
vpa	denotes vapor pressure of water at ambient temperature
w	denotes partial of water vapor in gas line
wa	denotes ambient partial pressure of water vapor in the air
ws	denotes partial pressure of water vapor at standard conditions
1	denotes absolute inlet pressure
2	denotes absolute outlet pressure
inlet	denotes absolute static heat at the gas release point
surface	denotes absolute pressure at the aeration tank water surface

pm = permeability coefficient
Q = volumetric flow rate
Q' = liquid flow entering and leaving the continuous flow reactor

SYMBOLS AND NOMENCLATURE (continued)

Subscripts Used with Q and Q'

a	denotes volumetric flow rate of air at standard conditions
das	denotes dry air portion of Q_a
dgs	denotes dry gas flow at 68°F and 14.70 psia
O	denotes volumetric flow rates of oxygen at standard conditions
r	denotes recycle sludge flow to the test volume
w	denotes flow rate for waste activated sludge

R = rate of oxygen consumption

Subscripts Used with R

b	denotes organism growth
s	denotes substrate utilization
N	denotes ammonia utilization

$\overline{R}$ = universal gas constant
R_e = pipe Reynolds number
r = oxygen activity coefficient
r_1 = inside radius of the cylinder
r_0 = outside radius of the cylinder
RH = relative humidity
S = concentration in the liquid phase of substrate
S_g = water specific gravity
SAE = standard aeration efficiency, aeration efficiency in clean water at standard conditions
SHP = shaft horsepower

Subscripts Used with SHP

F	denotes factory unit

SOTR = standardized OTR in clean water at stated conditions of T, DO, mixing, geometry, etc.
T = temperature

Subscripts Used with T

a	denotes ambient temperature
b	denotes base temperature
f	denotes flowing gas temperature
i	denotes inlet temperature
p	denotes pipe temperature

SYMBOLS AND NOMENCLATURE (continued)

T_q = torque
T_{qo} = zero-load torque for reaction load device
V = volume

Subscripts Used with V

A	denotes volume of aeration zone
B	denotes volume of accumulation zone
g	denotes reactor volume of the gas phase

V_G = temporal mean velocity gradient
W = oxygen transfer rate per unit volume in clean water

Superscript Used with W

^	denotes a localized point value

Subscript Used with W

f	denotes value applicable to dirty water field conditions

w_{da} = weight flow of dry air
w_{o_2} = weight flow of oxygen
X = concentration of biological organisms
$\overline{Y}$ = gas expansion correction factor
Y = mole fraction of oxygen in gas phase
Y_d = mole fraction of oxygen in the dry feed gas
Y_{das} = mole fraction of dry air at standard conditions
Y_e = mole fraction of oxygen in the exit gas
α = ratio of K_La in dirty water to K_La in clean water at equivalent conditions of T, geometry, mixing, etc.
α^* = ratio of K_La^* in dirty water to K_La^* in clean water at equivalent conditions of T, geometry, mixing, etc.
β = ratio of C^* in dirty water to C^* in clean water at equivalent conditions of temperature and partial pressure
γ = weight density

Subscripts Used with γ

a	denotes weight density of air at standard conditions
o	denotes weight density of oxygen at standard conditions
w	denotes weight density of water

SYMBOLS AND NOMENCLATURE (continued)

η_m = miscellaneous (bearings, etc.) efficiency of special factory hardware

Subscript Used with η_m

F	denotes factory unit

η_p = prime mover efficiency

Subscripts Used with η_p

F	denotes factory unit
I	denotes installation

η_R = reducer efficiency

Subscripts Used with η_R

F	denotes factory unit
I	denotes installation

θ = temperature adjustment factor defined so that:

$$\frac{(K_La) \text{ at } T_1}{(K_La) \text{ at } T_2} = \theta^{(T_1 - T_2)}$$

for equivalent conditions of geometry, mixing, partial pressure, and water quality

θ^* = temperature adjustment factor so that:

$$\frac{(K_La^*) \text{ at } T_1}{(K_La^*) \text{ at } T_2} = \theta^{(T_1 - T_2)}$$

Subscripts Used with θ

A	denotes arithmetic temperature correction
G	denotes geometric temperature

μ = absolute viscosity

ξ_{45} = strain at 45°

ρ = mass density

SYMBOLS AND NOMENCLATURE (continued)

Subscripts Used with ρ

a	denotes mass density of air at standard conditions
O	denotes mass density of oxygen at standard conditions
w	denotes mass density of water

τ = saturation temperature correction factor = C^*_T/C^*_{20}

$\bar{\tau}$ = tracer

ϕ_d = oxygenation coefficient

Ω = pressure correction

METRIC CONVERSIONS

CUSTOMARY UNIT				SI UNIT
Btu	x	1.055	=	kJ
Btu/lb	x	2.326	=	kJ/kg
cfm	x	4.719×10^{-4}	=	m^3/sec
cfs	x	0.02832	=	m^3/sec
cu ft	x	0.02832	=	m^3
cu ft	x	28.32	=	ℓ
°F		0.555(°F - 32)	=	°C
°C	+	273	=	K
ft	x	0.3048	=	m
ft-lb	x	1.356	=	J
gal	x	3.785	=	ℓ
gal	x	0.003785	=	m^3
gpm	x	6.308×10^{-5}	=	m^3/sec
gpm	x	0.06308	=	ℓ/sec
hp	x	0.7457	=	kW
hp-hr	x	2.685	=	MJ
in.	x	25.4	=	mm
lb (force)	x	4.448	=	N
lb (mass)	x	0.4536	=	kg
lb (mass)/hp-hr	x	0.6083	=	kg/kWh
lb/mil gal	x	0.1198	=	g/m^3
mil gal	x	3785	=	m^3
mgd	x	3785	=	m^3/day
mgd	x	0.0438	=	m^3/sec
pcf	x	16.02	=	kg/m^3
psf	x	0.04788	=	kN/m^2
psf	x	4.882	=	kgf/m^2

METRIC CONVERSIONS (continued)

CUSTOMARY UNIT				SI UNIT
psi	x	6.895	=	kN/m^3
psi	x	0.0703	=	kgf/cm^2
sq ft	x	0.0929	=	m^2
sq in.	x	645.2	=	mm^2
tons (short)	x	907.2	=	kg

ACKNOWLEDGEMENTS

This report represents the cooperative efforts of over 45 dedicated engineers, the members of the ASCE Oxygen Transfer Standards Subcommittee. It could not have been completed without their input during many long meetings and their critical review of all draft reports. The names of these members appear as Table 1 of this report.

The major authors of each section of this report are tabulated below. These individuals served as subgroup leaders and were the catalyst needed to complete the tasks.

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Section 5 - Unsteady State Clean Water Test
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Section 6 - Effects of Alpha, Beta, and Theta Factors and Surfactants on Specification, Design, and Operation of Aeration Systems
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Editing of the numerous reports submitted for this final report to the U.S. Environmental Protection Agency (EPA) has required many hours of effort. The Subcommittee is grateful for the technical editing that was so aptly provided by Laura Taylor, Edwin L. Barnhart and William C. Boyle.

Thanks are also in order to the ASCE administration, especially to Robert P. Morgan, Manager of Research and Standards Services, for his assistance in the many arrangements for meetings and the development of smooth communication between the Subcommittee and ASCE Headquarters.

Finally, special thanks are in order to the EPA Project Officer, Richard C. Brenner, who not only served as a technical Subcommittee member but also provided the Subcommittee with administrative assistance and editorial help on both this report and the workshop publication EPA-600/9-78-021, Workshop Toward an Oxygen Transfer Standard, which was an outgrowth of this current EPA project.

SECTION I

INTRODUCTION

Although considerable effort has been devoted to oxygen transfer technology over the years, it is evident that unanimity of opinion has not been achieved in the development of standard procedures for the evaluation of oxygen transfer devices. Presently, manufacturers rely on clean water shop tests for describing the oxygen transfer capability of aeration equipment. These capabilities are normally expressed as standardized oxygen transfer rates (SOTR) in clean water at zero dissolved oxygen (DO) at 20°C. Subtle differences in the method of data analysis can produce differences of 10 percent in the clean water SOTR. Moreover, this uncertainty is further magnified when translating clean water, test tank transfer rates to actual plant conditions. Because of differences in wastewater characteristics, tank geometry, wastewater temperature, mixing, and other system characteristics, uncertainties of up to 50 percent may be introduced.

Two common complaints voiced by engineers involved in aeration equipment design are the difficulties encountered in correlating manufacturers' oxygenation claims with shop or field test data and projecting equipment performance data to a respiring biological system in the field. The discrepancies between anticipated and actual performance are frequently sufficiently large to warrant substantial field modifications to the aeration equipment furnished. The cost of performing such modifications and the ill will generated offer excellent testimony to the need for a standardized method of oxygen transfer testing and data interpretation.

There is little question that a consensus standard is needed for oxygen transfer devices. Although several standard procedures are in existence, these procedures are concerned primarily with the methodology of experimental measurement and do not deal adequately with the interpretation and application of data to engineering design. Moreover, there is no general agreement among engineers and manufacturers as to which standard procedure or set of procedures to use. As a result, a wide variety of techniques are employed, resulting in substantial variations in test results for the same device in clean water tests. Even larger variations will be evident in translating these results to full-scale design. Only when standard procedures are developed through consensus agreement among experts in the field will a better degree of uniformity, accuracy, and economy result. Even then, continued updating of the standard will be required.

In an effort to obtain a consensus standard procedure for the evaluation of aeration devices, the American Society of Civil Engineers (ASCE) in January 1977 established a volunteer Subcommittee on Oxygen Transfer Standards (Table 1) under the Committee on Environmental Standards (Technical Council on Codes and Standards). Financial assistance was subsequently obtained from EPA to assist the Subcommittee in the development of first-phase interim standard procedures. The objectives of this project were to

1. review and critically evaluate the state-of-the-art of oxygen transfer testing,
2. evaluate and critically review existing testing standards and identify critical areas of disagreement and uncertainty,
3. develop documentation for recommendations for interim standard procedures and recommend verification methodology, and
4. prepare the proposed interim standard procedures.

Over the past 3 yr, this Subcommittee has been working towards these project objectives. This has been accomplished through Subcommittee deliberations and a sponsored workshop held in Asilomar, California, in April 1978. The Subcommittee was divided into subgroups with responsibilities for addressing five important areas: (1) oxygen transfer modelling and data interpretation, (2) unsteady state clean water transfer testing, (3) respiring systems oxygen transfer testing, (4) corrections for wastewater characteristics and temperature (alpha, beta, and temperature corrections), and (5) geometry and mixing considerations. Several Subcommittee members were later assigned the tasks for also evaluating methods for power and air flow measurements. The results of the deliberations of this Subcommittee are included within the text of this report. They represent a group effort based on the experience of experts in the field from industry, government,

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consulting firms, and universities. This report represents the first step in a series of steps necessary to develop an objective consensus standard for oxygen transfer devices.

PHILOSOPHY

In examining the objectives and procedures for testing oxygen transfer devices, the term standard as used within the context of this study refers to a methodology for (1) the measurement of the oxygen transfer capacity of equipment in clean water, (2) the interpretation of these test data, (3) the application of these data to engineering design of field oxygen transfer systems, and (4) on-site performance testing of oxygen transfer systems.

The Subcommittee has agreed that the development of a standard must be the outgrowth of an orderly process that includes a state-of-the-art assessment, development of a procedural manual, establishment of an interim standard or standards, and, if applicable, the final creation of a consensus standard or standards (Figure 1). The standardized protocols must include the details of the test procedures and methods of data analysis and uniform methods of calculation and data reporting. This Subcommittee was selected among experts in the field having a wide cross section of experience with oxygen transfer devices. It was clear early in its deliberations that a wide variety of opinions existed about the best methods for testing aeration

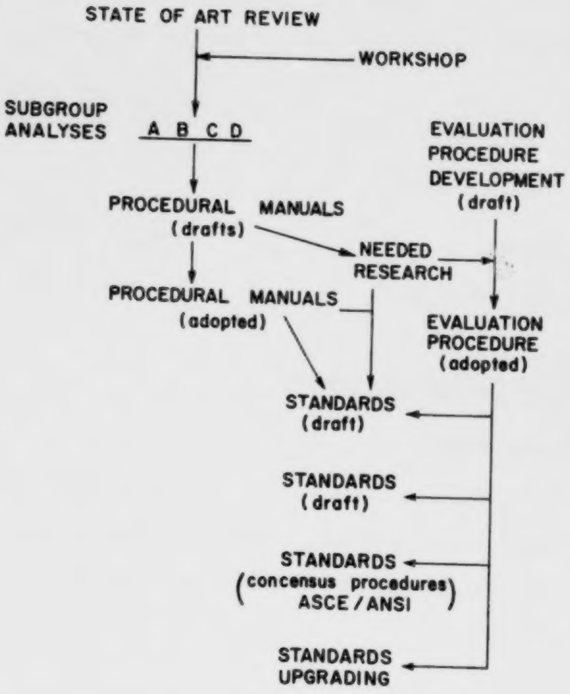
STATE OF ART REVIEW
WORKSHOP
SUBGROUP ANALYSES
A B C D
EVALUATION PROCEDURE DEVELOPMENT (draft)
PROCEDURAL MANUALS (drafts)
NEEDED RESEARCH
PROCEDURAL MANUALS (adopted)
EVALUATION PROCEDURE (adopted)
STANDARDS (draft)
STANDARDS (draft)
STANDARDS (concensus procedures ASCE/ANSI)
STANDARDS UPGRADING

Figure 1. Procedural Flowsheet-Subcommittee on Oxygen Transfer Standards.

equipment. These opinions were based on theoretical analysis, experience with shop testing of specific types of generic oxygen transfer equipment, and experiences with design and operation of field equipment. Rather than dismantle an existing standard, it was the decision of the Subcommittee that each aspect of the test procedures should be carefully reviewed and a state-of-the-art document developed that provided the pros and cons for current practice. Based on this state-of-the-art review, it was hoped that the Subcommittee would arrive at decisions on the best testing methods for oxygen transfer equipment as well as data evaluation techniques.

The proposed interim standard procedures as they appear within this report have been the outgrowth of several years of study, discussion, deliberation, and compromise. This Subcommittee is satisfied that these interim standard procedures represent the best state-of-the-art today.

Such procedures will be of little value to the profession, however, unless they are used and continuously critiqued. Only when standard procedures are developed through consensus agreement will a better degree of uniformity, accuracy, and economy result. Even then, continued updating of the standard will be required. This Subcommittee will continue to function as a standards development and review group under the ASCE Technical Council on Codes and Standards.

FORMAT OF THIS REPORT

This report is presented as a series of interdependent topics dealing with the testing and application of oxygen transfer devices. Three of these sections (Sections 4, 5, and 7) present recommended procedures for testing oxygen transfer devices and analyzing the data resulting therefrom and document the development of these recommendations. Four other sections (Sections 6, 8, 9, and 10) provide supplementary information required for the interpretation and application of the standard procedures to field design. Finally, Section 11 briefly describes proposed methods for the evaluation of the proposed standard procedures.

SECTION 2

CONCLUSIONS

The ASCE Oxygen Transfer Standards Subcommittee has made an exhaustive review of the methods used for the testing of oxygen transfer devices. This study included reviews of

1. modelling and data interpretation,
2. clean water unsteady state testing,
3. oxygen transfer measurements in respiring systems,
4. impacts of wastewater characteristics and temperature on oxygen transfer,
5. effects of geometry and mixing on oxygen transfer, and
6. methods of air flow and power measurements.

Based on these reviews, recommended procedures have been presented for the testing of oxygen transfer devices in both clean and dirty water. These recommended procedures are delineated under the appropriate sections of this report. To list separate, more abbreviated conclusions from this comprehensive study is unwarranted since they would be out of context and may be misinterpreted.

SECTION 3

RECOMMENDATIONS

A review of state-of-the-art procedures for oxygen transfer testing and subsequent recommendations for interim standardized procedures for that testing represents the first step in an orderly procedure for developing a consensus standard. It is now necessary to evaluate the proposed interim standard procedures through field testing over a wide variety of conditions.

A proposed field testing program is described in Section 11 of this report. Verification testing would ideally include testing for both accuracy and precision. Precision of the proposed procedures can be obtained through replicate testing, again under a variety of conditions with a variety of oxygen transfer devices. Accuracy, on the other hand, requires a standard against which the procedures can be compared. Unfortunately, no acceptable standard for oxygen transfer exists at this time. It has been suggested that a tracer technique using either a radioactive or nonradioactive isotope of krypton serve as that standard.

The translation of clean water tests to field conditions still requires a great deal of work. Currently, engineers employ corrections for wastewater characteristics (alpha and beta), wastewater temperature (theta), and geometry and mixing. These corrections are currently based upon experience. Laboratory tests for alpha do not appear reliable, and rule-of-thumb corrections for scale-up of geometry, power levels, etc., are not entirely satisfactory at this time. Field and laboratory research are, therefore, essential to improve our ability to scale up clean water test data to field conditions.

The adoption by the profession of standardized procedures for the testing of oxygen transfer devices is the first important step in achieving answers to many questions that still remain regarding the design, operation, and control of aeration systems. Once standardized procedures against which comparisons can be made become recognized throughout the field, corrections for translation of clean water performance to dirty water performance can be more clearly studied. The net result will be more accurate designs of aeration systems with savings in both capital and energy for the owner.

SECTION 4

MODELLING AND DATA INTERPRETATION

RECOMMENDED STANDARD METHOD FOR MODELLING AND ANALYZING UNSTEADY STATE TEST DATA

The Model

The basic model recommended for the analysis of both surface and subsurface clean water, unsteady state oxygen transfer test data is:

$$\frac{dC}{dt} = K_La(C^*_\infty - C) \qquad \text{(differential form)} \qquad (1)$$

which, upon integration, becomes:

$$\ln\left(\frac{C^*_\infty - C}{C^*_\infty - C_0}\right) = -K_La\,t \qquad \text{(logarithmic form)} \qquad (2)$$

or:

$$C = C^*_\infty - (C^*_\infty - C_0)\exp(-K_La\,t) \qquad \text{(exponential form)} \qquad (3)$$

where:

C^*_∞ = average dissolved oxygen (DO) saturation concentration attained at infinite time, m/L^3

K_La = apparent volumetric mass transfer coefficient, t^{-1}

C_0 = DO concentration at t = 0, estimated from the model, m/L^3

C = effective average DO concentration in the liquid phase, m/L^3

t = time, t

and the symbols m, L, t, and f are employed to denote dimensions of mass, length, time, and force, respectively.

This model applies to a given aeration system in a given tank under steady state hydraulic conditions. It is shown in the Commentary that this model can be viewed either as based on a completely mixed system with uniform

DO values in which oxygen is transferred throughout the tank volume or as based on a compartmentalized system in which oxygen transfer is confined to a localized aeration zone. The compartmentalized system allows for nonuniform DO concentration values in the accumulation zone but does require that the average DO value of the aeration zone equal the effective average of the accumulation zone. Although this equality seems reasonable, it has not been verified experimentally. Consequently, additional uncertainty is introduced when the recommended model is applied to a system in which appreciable differences exist between values of DO measured at different points in the tank.

In both cases, the average DO concentration, C, represents a bulk average, i.e.:

$$C = \frac{\int \hat{C}\, dV}{V} \tag{4}$$

where:

$\hat{C}$ = localized DO concentration, m/L^3

V = portion of the volume over which C is averaged, L^3

It follows that, if the results of multiple sample points are to be analyzed by a simple average, the sample points should be chosen so that each senses an equal portion of the tank volume.

In the application of this model to unsteady state test data, it is recommended that:

1. The exponential form should be employed and fit to the test data by nonlinear regression.

2. Values of the parameters K_La, C^*_∞, and C_0 should be estimated from the model. Individual measured values of C^*_∞ and C_0 are not to be used as model parameters. Likewise, tabulated book values of DO surface saturation concentrations are not to be used to estimate C^*_∞.

3. An effort should be made to gather valid DO data over as wide a range as possible. Truncation of data at values of C less than 20 percent of C^*_∞ is allowable to avoid lingering effects of the deoxygenation technique. However, good data at low DO values should be used in the estimation because they are important for assessing model adequacy. A guideline that may be applied for more precise determination of the low truncation point when sampling intervals are small is to locate an inflection point by

differentiating the data and truncating data at C values below 1.5 times the C at the inflection point. However, in no case should values of C greater than 30 percent of C^*_∞ be truncated.

Truncation data at DO values approaching C^*_∞ is strongly discouraged and is recommended only when the alternate Best Fit Log Deficit Method is employed.

4. When lack of a computing facility prevents the application of non-linear regression to the exponential form of the model, a linear regression applied to the logarithmic form of the model is an acceptable alternate technique. When this technique, termed the Best Fit Log Deficit Method is used, the value of C^*_∞ is to be estimated from the model as the value giving the minimum residual sum of squares on the log deficit plot.

5. In most cases, calculation of standard clean water and dirty water respiring system oxygen transfer rates (SOTR and OTR_f values) should be based on the estimated values of K_La and C^*_∞ along with given or separately determined values of α, θ, and β. This approach is relatively straightforward and simple. However, it is acceptable to base the calculations of SOTR and OTR_f on a "true" volumetric mass transfer coefficient, K_La^* In this case, values of α and θ based on ratios of K_La values should be distinguished from values of α^* and θ^* based on K_La^* values.

Parameter Estimation

Inspection of the Data --

Prior to a numerical analysis, it is recommended that the data be plotted, preferably as DO concentration versus time. The plotted data should be examined on two accounts. First, the data should be inspected for trends indicative of a departure from the assumed exponential form of Equation 3. Typical examples of this phenomenon are a lag period at the beginning of reaeration or a ramp-type trend in the data. Second, an assessment of the noise in the data should be made. A spurious data value of especially noisy observations may be indicative of poor experimental procedures. If any anomalies are observed in the data record, the reasons should be noted and a determination made whether or not to discard spurious data prior to proceeding with the numerical analysis. The Data Trunction and Model Adequacy subsection of this section discusses methods for handling some of the minor model inadequacies and noisy data.

Recommended Parameter Estimation Procedure --

The model in exponential form given by Equation 3 is best suited to the analysis of unsteady state oxygen transfer data. The use of this equation for parameter estimation requires that the data be in the form of DO concentration versus time. It is recommended that the parameters C_0, K_La, and C^*_∞ be estimated using a nonlinear least squares regression technique. The advantages of this approach are:

1. It provides the least squares estimates and precision of these estimates for all three parameters directly from the data.
2. It works directly with the observed DO concentration, C, rather than with a calculated DO deficit or with an approximation to the time rate of change of oxygen concentration.
3. It does not require the truncation of observed data as the DO concentration approaches saturation.
4. For a given set of data, it should provide parameter estimates that are more precise than those given by other commonly used methods.

There are two disadvantages to this procedure, but neither is felt to be severe.

1. The method employs an iterative search for the least squares estimates; thus, for practical purposes, the use of a computer (or advanced scientific calculator) is required for parameter estimation.
2. Because of the nature of the error structure of DO concentration versus time data, the use of Equation 3 for parameter estimation may overweight the observations at the beginning of the test in systems where transfer rates are high. Weighting procedures designed to overcome this difficulty have been suggested, but they do not offer a clear advantage over the unweighted analysis.

Various techniques for performing nonlinear regression analysis of unsteady state oxygen transfer test data using Equation 3 are described in Appendix A and the Commentary. These techniques provide least squares estimates of C_0, C^*_∞, and K_La. In addition to the least squares estimates, the standard deviation or relative standard deviation of the parameter estimates should be calculated and reported. This calculation is incorporated into many of the available computer programs for nonlinear parameter estimation. The values of the standard deviations reflect the degree of scatter in the test data and should be small for a good test. Acceptable values for shop tests are 5 percent for K_La, 3 percent for C^*_∞, and 0.3 mg/ℓ for C_0. Also, the error structure of the data should be examined by a plot of the residuals (the difference between observed and predicted DO concentrations). Trends in the residuals may reveal possible hydrodynamic irregularities such as surging and macroscopic mixing patterns. More importantly, however, the residuals provide information about the uniformity and magnitude of experimental error and about the adequacy of the model to describe the observed data.

A Fortran computer program for performing nonlinear regression analysis of unsteady state oxygen transfer data using Equation 3 is described in Appendix A. The program employs an iterative linearization method to search for the best parameter values. The program calculates the least squares estimates and approximate standard deviations of C_0, C^*_∞, and K_La and computes the residuals for a check on model adequacy.

Alternate Parameter Estimation Procedure: Best Fit Log Deficit Method --

Although the nonlinear regression method using Equation 3 is the recommended standard for parameter estimation, the Best Fit Log Deficit Method based on Equation 2 is acceptable when lack of a computing facility prevents application of the recommended method. In this technique, the value of C^*_∞ is estimated from the model as that giving the minimum residual sum of squares on the log deficit plot. The chief advantage of this approach is that it can be applied by using an ordinary scientific calculator instead of the computer required in the recommended method.

However, this approach has several disadvantages:

1. It consists of successive trial and error regression analyses, i.e., a separate regression analysis must be performed, and the residual sum of squares must be calculated for each trial value of C^*_∞. Because of this, it is time consuming and tedious.

2. The logarithmic transformation weights the data and is proper only when the experimental error is a constant percentage of the deficit.

3. Data truncation is required as DO values approach saturation in

order to avoid taking logs of negative numbers. It is recommended that DO values observed at times greater than approximately $3/K_La$ (95 percent saturation) be truncated.

4. This method is basically a one parameter estimate, and, therefore, standard errors of estimate comparable to those of the recommended nonlinear method are not readily calculated.

Other Parameter Estimation Methods --

Other methods employing graphical and/or linear least squares numerical techniques may be useful for obtaining approximate values of the parameters. Several variations of the log deficit method have been applied to analyze unsteady state test data. The variations here are related primarily to the selection of C^*_∞ and degree of data truncation practiced.

Possibilities for the selection of C^*_∞ include

1. use of a single or average measured value,
2. use of a book surface saturation value corrected to mid or some other depth,
3. use of a book surface saturation value corrected for depth and exit gas depletion, and
4. estimation of C^*_∞ from the model as the value giving either the "straightest" line or the minimum residual sum of squares (as in the recommended alternate Best Fit Log Deficit Method).

The disadvantage of approach 1 above is that the measured value will include error and bias the estimate of K_La. However, based on the work of Ewing et al.,[1] it appears that this approach applied to good data yields results close to those of the recommended method. This approach has been applied by several investigators.[2,3,4,5]

Approaches 2 and 3, based on corrected surface saturation values, can severely bias the parameter estimates. Furthermore, it must be realized that the exit gas depletion correction will produce an estimate of K_La^* rather than K_La. These approaches are not recommended.

Approach 4 generally yields results close to those of the recommended method and is acceptable as an alternate to the recommended nonlinear regression approach. Campbell[6] applied this approach to analyze unsteady state oxygen transfer data.

All of the log deficit approaches suffer from the necessity to truncate the data at values of C approaching C^*_∞. In addition, this method does not enable the precision of C^*_∞ to be estimated.

The direct method is based on graphical or numerical differentiation of the C versus t data in order to determine $\frac{dC}{dt}$. Values of both K_La and C^*_∞ are then obtained directly from a plot of $\frac{dC}{dt}$ versus C. This method has the advantage of being able to estimate two parameters. However, the differentiation inherent in the direct method produces a variable $\frac{dC}{dt}$ having a larger error than the error in C. The larger error in $\frac{dC}{dt}$ causes the error in the parameter estimates, C^*_∞ and K_La, to be larger than those from the other methods.

The recommended nonlinear regression method requires that initial estimates of the parameter values be provided. The log deficit and/or direct methods are useful procedures for obtaining those initial parameter values.

Experimental Design

It is recommended that unsteady state oxygen transfer tests be conducted for as long a period of time as practicable. A minimum period of time approximately equal to 4 divided by the anticipated value of K_La is suggested. This value corresponds to a DO concentration of 98 percent of C^*_∞. When it is practical, the test should be run to $6/K_La$ for the record and for comparison with the estimated C^*_∞ value. For reference, Table 2 gives the relationship between time in multiples of reciprocal K_La and DO concentration in terms of percent of C^*_∞ for Equation 3.

It is recognized that temperature variations may affect the precision and accuracy of the test. Therefore, as a minimum, it is suggested that the water temperature and barometric pressure be measured at the beginning and end of the test. The average temperature and pressure during the test along with the beginning and ending values should be reported with the results.

It is recommended that the regression analysis be based on a minimum of 10 to 15 data values. Analysis with fewer than 10 data values will reduce the precision of the parameter estimates and will impair the ability to assess model inadequacy if it is present. Analysis with more than about 20 data values usually does not result in a significant improvement in the precision of the parameter estimates and may weaken the assumption of

TABLE 2. RELATIONSHIP BETWEEN TIME AND PERCENT SATURATION FOR EQUATION 3*

Time as Multiples of $1/K_La$	DO Concentration as Percent of C^*_∞
0	0
0.1	9.5
0.2	18
0.5	39
0.7	50
1.0	63
1.5	78
2.0	86
2.5	92
3.0	95
4.0	98
5.0	99
6.0	99+

*C_0 is assumed to be zero.

independence among the observations. Approximately two-thirds of these values should be evenly distributed over the period of time between the initial data point which is above zero and $2/K_La$. The remaining one-third of the values should be evenly distributed over the period of time covered by $2/K_La$ to $4/K_La$. In cases of rapid transfer, the maximum time between observations should normally be 0.4 min.

In systems using multiple sampling locations, the data from each sample point should be analyzed separately and values of the parameters should be estimated and reported for each sampling point. The uniformity of the separate estimates may provide useful information about the variation of transfer characteristics within the aeration system. The average value of each parameter will provide information about the overall transfer characteristics of the aeration system.

Data Truncation and Model Adequacy

Truncation of data as the DO concentration approaches saturation is discouraged because these data significantly influence the parameter estimates of K_La and C^*_∞. This is the reason for recommending that the test be conducted to at least a time approximating $4/K_La$ (98 percent of C^*_∞).

Truncation of the data at low DO values presents a different problem. Values of DO concentration less than 10 to 30 percent of saturation, C_{∞}^{*}, may have to be truncated to avoid lingering effects of the deoxygenation technique. However, data values in this range are important in determining whether the model given by Equation 3 is adequate. If model inadequacy is to be manifested, it would be expected during the early portion of the unsteady state test.

The precision of the least squares estimate of C_0 as well as a plot of the residuals versus time should yield meaningful information about model adequacy. Thus, it is recommended that valid DO observations be recorded as close to zero as possible while still avoiding the influence of deoxygenation. A decision on model adequacy is subjective and normally requires a rigorous statistical analysis. However, a general indication may be obtained by comparing the estimate of error from the statistical fit of the model (the square root of the residual mean square) with the experimental error (sampling plus analytical error) in measuring DO in the test system. If the estimate of error from the residuals is more than twice the experimental error estimate, then model inadequacy may be indicated. As previously stated, Equation 3 will adequately model the great majority of aeration devices commonly employed in wastewater treatment systems. In the event that the residual plot or the error analysis indicates that this model is clearly inadequate, one of two approaches may be followed:

1. A more refined mechanistic model such as a variable gas rate model[1] may be investigated. However, the more sophisticated models generally present more difficult parameter estimation problems and care must be taken to correctly interpret and apply the resulting parameter estimates.

2. More severe data truncation may be applied in an attempt to produce a better fit of the model to the data in the region of greatest interest. However, this truncation tends to lower the precision of the parameter estimates and the resulting uncertainty should be considered in interpreting the results.

Interpretation and Reporting of Results

Recommended Method: Surface and Submerged Aeration --

By convention, the oxygen transfer capacity of an aeration system is usually expressed as the rate of oxygen transfer predicted by the model at zero DO under standard conditions of water temperature and pressure, usually 1.0 atmosphere at a specified relative humidity and 20°C. This is termed the standardized oxygen transfer rate (SOTR). It should be noted that the SOTR is a hypothetical value based on zero DO in the aeration zone, which is not usually desirable in real aeration systems operating in process water. The SOTR value can be determined by correcting the test values of K_La and C^*_∞ to standard conditions by:

$$K_La_{20} = K_La_T\theta^{(20-T)} \tag{5}$$

$$C^*_{\infty 20} = C^*_{\infty T}\left(\frac{C^*_{s20}}{C^*_{sT}}\right)\left(\frac{p_s + \gamma_w d_e - p_{v20}}{p_b + \gamma_w d_e - p_{v20}}\right) \tag{6}$$

where:

θ = empirical temperature correction factor ranging from 1.015 to 1.03, usually = 1.024

C^*_{sT} = DO surface saturation book value at the test temperature, m/L^3

p_s = standard atmospheric pressure, usually 1.00 atm., air at 100 percent relative humidity, f/L^2

p_b = atmospheric pressure during test, f/L^2

p_v = saturated vapor pressure of water, f/L^2

d_e = effective saturation depth at infinite time, L, defined by

$$d_e = \frac{1}{\gamma_w}\left(\frac{C^*_{\infty T}}{C^*_{sT}}(p_s - p_{vT}) - p_b + p_{vT}\right)$$

γ_w = weight density of water, m/L^3

and the subscripts T and 20 denote the quantity evaluated at the test and 20°C water temperatures, respectively.

The SOTR is then computed by:

$$\text{SOTR} = K_La_{20}\, C^*_{\infty 20}V \tag{7}$$

where:

V = volume of water in the test tank, L^3

It is recommended that the values of K_La_{20}, $C^*_{\infty 20}$, θ, V, and the actual test temperature be reported along with the SOTR. If possible, the standard deviations of the K_La, C^*_∞, and C_0 parameter estimates should also be reported.

Frequently, the standardized aeration efficiency (SAE) or rate of oxygen transfer per unit power input is of interest and can be computed from:

$$SAE = \frac{SOTR}{\text{Power Input}} \tag{8}$$

This parameter is normally expressed in units of pounds per horsepower hour or kilograms per kilowatt hour.

Alternate Method --

An alternate approach, applicable to subsurface gas injection systems only, recognizes that, because of oxygen depletion in the rising gas stream, the true value of the volumetric mass transfer coefficient, K_La^*, is somewhat larger than the apparent value of K_La. The calculation is complicated by the fact that the temperature correction factor, θ, and the value of α are usually given as ratios of K_La values and must be adjusted before applying them to K_La^* values. When the values of α and θ are properly adjusted, this approach will give standardized and field oxygen transfer rates closely approximating those given by the recommended procedure.

As outlined in the Commentary, this approach is based on the transfer equation, the gas side oxygen balance, and an assumed relationship between C^* (see Commentary for definition) and the oxygen content of the feed and exit gases. Different models arise when various approximations are made in the gas side oxygen balance and various assumed relationships are employed.[7] One model, similar to that proposed by Downing and Boon[8] and later applied by Ewing et al.,[1] in particular, is attractive because it reduces to the form of Equations 1 to 3 and is amenable to the same parameter estimation methods. An acceptable alternate method of calculating SOTR values by this model is illustrated at the end of this section.

Application of Clean Water Test Data to Dirty Water Respiring Systems

Recommended Method --

For given values of α, β, temperature, θ, DO concentration, and barometric pressure, the clean water SOTR is related to an actual dirty water transfer rate in a respiring system by:

$$OTR_f = \frac{\alpha(SOTR)\theta^{(T-20)}}{C^*_{\infty 20}}(\tau\beta\Omega C^*_{\infty 20} - C) \qquad (9)$$

where:

OTR_f = oxygen transfer rate in the dirty water respiring system, m/T

Ω = pressure correction = $\dfrac{P_b + \gamma_w d_e - P_{v20}}{P_s + \gamma_w d_e - P_{v20}}$

τ = temperature correction = $\dfrac{C^*_{sT}}{C^*_{s20}}$

$\alpha = \dfrac{\text{dirty water } K_La}{\text{clean water } K_La}$

$\beta = \dfrac{\text{dirty water } C^*_\infty}{\text{clean water } C^*_\infty}$

An acceptable alternate method based on K_La^* corrected for gas side oxygen depletion is outlined in the example problem at the end of this section.

COMMENTARY ON THE RECOMMENDED STANDARD METHOD

Models

Theoretical Development --

Fundamental relationships -- The basic model for oxygen transfer in a dispersed gas-liquid system is given by:

$$\begin{pmatrix}\text{Rate of Mass Transfer}\\ \text{per Unit Volume of}\\ \text{Liquid}\end{pmatrix} = \begin{pmatrix}\text{Volumetric}\\ \text{Mass Transfer}\\ \text{Coefficient}\end{pmatrix} \times \text{Driving Force} \qquad (10)$$

Expressed in terms of the overall liquid phase volumetric mass transfer coefficient, this relationship becomes:

$$\hat{W} = \hat{K}_L\hat{a}^*(\hat{C}^* - \hat{C}) \qquad (11)$$

where the ^ superscript is employed to indicate the local nature of the quantities and:

W = oxygen transfer rate per unit volume in clean water, $mL^{-3}t^{-1}$

K_L* = true overall liquid phase mass transfer coefficient, based on the liquid resistance, L/t

a = interfacial surface area per unit volume, L^{-1}

$\hat{C}$* = point value of DO saturation corresponding to a given oxygen partial pressure and water temperature, m/L^3

In applying Equation 11 to an oxygen transfer system, it must be remembered that this relationship applies to a particular point. In general, the total rate of oxygen transfer is of interest and can be evaluated by integrating the local transfer rate over the volume, V:

$$WV = \int \hat{W}\, dV = \int \hat{K}_L a^*(\hat{C}^* - \hat{C})dV \qquad (12)$$

Clearly, $\hat{K}_L$*, $\hat{a}$, $\hat{C}$*, and $\hat{C}$ may vary over the volume. Different assumptions made concerning the spatial and temporal variation of these quantities constitute the main differences between the various models applied to oxygen transfer systems.

Application of fundamental relationships to oxygen transfer systems -- The manner in which Equation 12 is applied to an oxygen transfer system depends on the characteristic of that system. Of particular importance are the spatial variations in DO concentration and transfer rate as influenced by geometry and mixing within the system. The following two idealized systems will be considered.

Completely mixed system --- This system is idealized as a completely mixed tank in which oxygen is transferred throughout the volume with C and K_La* being uniform throughout the volume. In this case, Equation 10 can be integrated over the tank volume, with $W = \frac{dC}{dt}$, to give:

$$\frac{dC}{dt} = K_L a^*(C^* - C) \qquad (13)$$

where:

C* = effective average DO saturation concentration defined by

$$C^* = \frac{\int_V \hat{C}^* dV}{V} \qquad (14)$$

Baillod[7] reviewed various approaches to relate C* to the inlet and exit oxygen content of the aeration gas in terms of Henry's law constant and the effective saturation depth.

Compartmentalized system --- This system is idealized as a tank in which oxygen transfer is confined to a localized aeration zone to which uniform average values of $K_La_a^*$, C*, and C may be applied. The remainder of the tank serves as an accumulation zone in which DO concentration gradients may exist.

Figure 2 shows a profile of the idealized compartmentalized system. Fluid circulates through each zone at a volumetric flow rate, Q. Oxygen transfer takes place primarily in the aeration zone, which would correspond to the spray of a surface aerator or to the zone directly above the diffusers in a spiral flow system. The fluid leaves the transfer zone and circulates through the accumulation zone without additional oxygen transfer taking place during circulation.

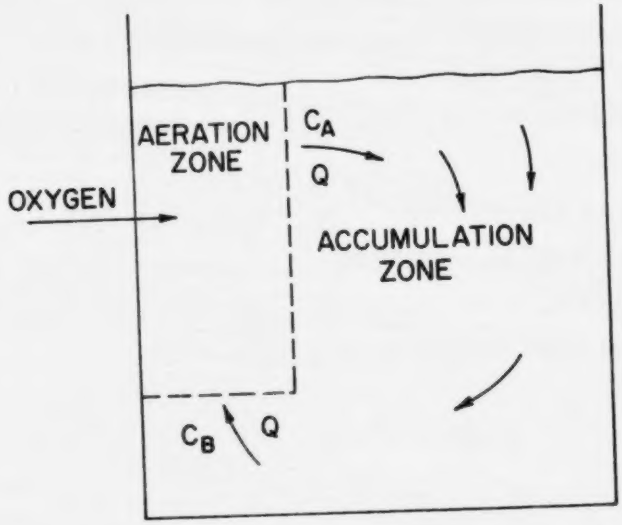

Figure 2. Profile of an oxygenation tank.

Oxygen balances can be written on the liquid in each zone during an unsteady state clean water test as:

Aeration Zone:

$$Q(C_B - C_A) + V_A K_L a_a^{*}(C^{*} - C_{AB}) = V_A\left(\frac{dC_{AB}}{dt}\right) \tag{15}$$

Accumulation Zone:

$$Q(C_A - C_B) = V_B\left(\frac{dC}{dt}\right) \tag{16}$$

where:

Q = volumetric pumping rate of aerator, L^3/t

C_B = DO concentration in flow entering the aeration zone, m/L^3

C_A = DO concentration in flow leaving the aeration zone, m/L^3

V_A = volume of aeration zone, L^3

V_B = volume of accumulation zone, L^3

$K_L a_a^{*}$ = true volumetric mass transfer coefficient applicable to the aeration zone volume, t^{-1}

C_{AB} = effective average DO concentration in the aeration zone, m/L^3, defined by $WV_A = V_A K_L a_a^{*}(C^{*} - C_{AB})$

C = average DO concentration in the accumulation zone, m/L^3

Combining Equations 15 and 16 gives:

$$\left(\frac{V_A}{V_B}\right)\left(\frac{dC_{AB}}{dt}\right) + \frac{dC}{dt} = \left(\frac{V_A}{V_B}\right) K_L a_a^{*}(C^{*} - C_{AB}) \tag{17}$$

If it is assumed that $C = C_{AB}$, Equation 17 reduces to:

$$\frac{dC}{dt} = K_L a^{*}(C^{*} - C) \tag{18}$$

where:

$K_L a^{*}$ and $K_L a_a^{*}$ are related by:

$$K_L a^{*} = K_L a_a^{*}\left(\frac{V_A}{V_A + V_B}\right) \tag{19}$$

Comparison of Equations 13 and 18 indicates that the analysis of each system leads to the same result. The subtle difference between the equations is that in the development of Equation 13, C and $K_L a^{*}$ were assumed to be uniform over the entire tank volume, whereas Equation 15 assumed uniformity only over the aeration volume.

The assumption of $C_{AB} = C$ seems reasonable but has not been experimentally established for typical systems. Lack of agreement between these concentrations would require that Equation 17 be applied to analyze unsteady state test data. In doing this, care would be required in the definition and measurement of C_{AB}, the effective average DO concentration in the aeration zone. It appears that this is an area in which further research is warranted.

The recommended model (Equation 3) is based on Equations 13 and 18 and can be applied to situations meeting the assumptions inherent in the development of either of these equations. In many systems, aerator placement and tank geometry produce a completely mixed system and the recommended model may be logically applied based on Equation 15. In other cases, however, localized aeration zones may cause nonuniform DO values and the recommended model is viewed as based on the compartmentalized system (Equation 18). Additional uncertainty is introduced here by the unverified assumption that $C = C_{AB}$.

In the case of a steady state compartmentalized respiring system, inclusion of the biological oxygen uptake rate R (mass of oxygen per unit volume per unit time) into the material balance equation (Equations 15 and 16) yields:

$$R = K_L a^*(C^* - C) \qquad (20)$$

where:

R = volumetric uptake rate due to biological respiration in both the aeration and accumulation zones, $mL^{-3}t^{-1}$

This development is predicated upon equal uptake rates in the aeration and accumulation zones, an occurrence which is reasonable only if DO is actually present (at concentrations in excess of values that limit R) in all regions of both zones. It follows that application of the compartmentalized model to predict transfer rates in respiring systems will be valid only when the DO concentration is above zero in all regions of the accumulation zone.

Although the SOTR is a convenient parameter for applying clean water data to field conditions, it should be remembered that application of the model to a respiring system described by the compartmentalized model requires that DO be present in all regions of the accumulation zone. Because of this, it is incorrect to calculate oxygen transfer rates based on SOTR values for compartmentalized systems unless the average operating DO value in the accumulation zone is great enough to avoid oxygen limitation on uptake rates.

Unsteady state models -- Most analyses of unsteady state aeration are based on Equation 18.

In submerged aeration, C* varies with time during the unsteady state test. Therefore, it is necessary to incorporate two additional relationships into a submerged aeration model based on this equation. One of these arises from a gas side oxygen balance and relates the oxygen content of the feed and exit gases in terms of the gas feed rate and transfer rate:

$$\left(\frac{M_o}{M_a}\right) G_F Y_d - \left(\frac{M_o}{M_a}\right) G_E Y_e = V\left(\frac{dC}{dt}\right) \qquad (21)$$

where:

M_o, M_a = molecular weights of oxygen and air, respectively, m/mol
G_F, G_E = mass rates of feed and exit gases, respectively, m/t
$G_F = \rho_{ad}\, Q_{ad}$
$G_E = \rho_{ae}\, Q_{ae}$
Y_d, Y_e = mole fractions of oxygen in the dry feed and exit gases, respectively
ρ_{ad}, ρ_{ae} = mass densities of feed and exit gases, respectively, m/L^3
Q_{ad}, Q_{ae} = volumetric flow rates of feed and exit gases, respectively, L^3/t.

The other equation relates C* to the oxygen content of the feed and exit gases. Baillod[7] has reviewed various relationships employed for this purpose. One such relationship, similar to that proposed by Downing and Boon[8] and used subsequently by Ewing et al.[1] is:

$$C^* = \frac{(Y_d + Y_e)}{2}\,(p_b - p_v + \gamma_w d_e)\overline{H} \qquad (22)$$

where:

d_e = effective saturation depth, L
$\overline{H}$ = Henry's law constant, conc/mol fraction/pressure

At infinite time in the unsteady state test, $C^* = C^*_\infty$ and $Y_e = Y_d$, so that:

$$C^*_\infty = Y_d(p_b - p_v + \gamma_w d_e)H \qquad (23)$$

A reasonable approximation for most aeration systems is that the feed and the exit gas rates are equal, or that $G_F \approx G_E$. With this approximation, Equations 13 or 17 and 21 to 23 can be combined to give:

$$\frac{dC}{dt} = \left(\frac{K_La^*}{1 + K_La^*/2\phi_d}\right)(C^*_\infty - C) \tag{24}$$

where:

ϕ_d = oxygenation coefficient, t^{-1}, = $\frac{(M_o/M_a)G_F\, Y_d}{C^*_\infty V}$

$\frac{K_La^*}{\phi_d}$ = transfer number, dimensionless, = $\frac{K_La^* C^*_\infty V}{(M_o/M_a)G_F\, Y_d}$

Comparison of Equations 1 and 24 shows that the "true" and "apparent" values of K_La are related by:

$$K_La^* = \frac{K_La}{1 - \frac{K_La}{2\phi_d}} \tag{25}$$

Here, the apparent transfer number, K_La/ϕ_d, is equal to the oxygen transfer efficiency at zero DO concentration, OTE_o:

$$\frac{K_La}{\phi_d} = \frac{K_La\ C^*_\infty\ V}{(M_o/M_a)G_F\ Y_d} = \frac{\underline{\text{oxygen transfer rate at zero DO}}}{\text{oxygen supply rate}} = OTE_o \tag{26}$$

Typical values of the oxygenation coefficient, ϕ_d, are on the order of 0.75 min^{-1}, whereas typical values of K_La are on the order of 0.15 min^{-1}, giving typical values of the apparent transfer number, or OTE_o, on the order of 0.2. Therefore, typical values of the "true" K_La, K_La^*, would be about 10 percent greater than those of the "apparent" K_La. However, for high efficiency subsurface aeration systems, OTE_o may approach 0.5 and the two values of K_La could differ by more than 30 percent.

Field Application to Respiring System --

Influence of water characteristics and water temperature -- To apply clean water test parameters to the design or evaluation of dirty water respiring systems, it is necessary to correct for the influence of water characteristics and water temperature on the transfer coefficient and saturation value. The effect of water characteristics is accounted for by the so-called alpha and beta factors, defined here in terms of "true" K_La, K_La^*, by:

$$\alpha^* = \frac{\text{dirty water } K_La^*}{\text{clean water } K_La^*} = \frac{K_La^*_f}{K_La^*} \qquad (27)$$

$$\beta = \frac{\text{dirty water } C^*}{\text{clean water } C^*} = \frac{C^*_f}{C^*} \qquad (28)$$

where the subscript f denotes the dirty water field condition. It is reasonable to expect that the influence of dirty water on the various saturation values will be similar, so that:

$$\frac{C^*_f}{C^*} = \frac{C^*_{\infty f}}{C^*_\infty} = \frac{C^*_{sf}}{C^*_s} = \beta \qquad (29)$$

Likewise, the influence of temperature on the transfer coefficient and saturation value can be expressed in terms of the factors theta and tau, defined by:

$$\theta^{*(T-20)} = \frac{K_La^*_{fT}}{K_La^*_{f20}} \qquad (30)$$

$$\tau = \frac{C^*_T}{C^*_{20}} \qquad (31)$$

where the subscript T denotes field temperature. Again, it is reasonable to expect that the influence of temperature on the various saturation concentrations will be similar, so that:

$$\frac{C^*_T}{C^*_{20}} = \frac{C^*_{\infty T}}{C^*_{\infty 20}} = \frac{C^*_{sT}}{C^*_{s20}} = \tau \qquad (32)$$

This relationship allows the value of τ to be determined from the ratio of published surface saturation values.

The relationships given by Equations 27 and 30 are based on "true" K_La, K_La^*, values, and it has been shown that values of the "apparent" and "true" K_La may differ by 30 percent. Because of this, it is necessary to define an "apparent" alpha, α, by:

$$\alpha = \frac{\text{dirty water } K_La}{\text{clean water } K_La} = \frac{K_La_f}{K_La} \qquad (33)$$

and an "apparent" theta, θ, by:

$$\theta^{(T-20)} = \frac{K_La_{fT}}{K_La_{f20}} \qquad (34)$$

Finally, it is necessary to correct C* for differences in atmospheric pressure between the test, standard, and field conditions. The value of C* is not a linear function of total atmospheric pressure, but is a linear function of the partial pressure of dry air at the saturation depth. Therefore, the pressure correction factor, Ω, is defined as:

$$\Omega = \frac{C^*_\infty \text{ at } p_b}{C^*_\infty \text{ at } p_s} = \frac{p_b + d_e - p_v}{p_s + d_e - p_v} \qquad (35)$$

where the various terms are as defined earlier.

Alternate approaches based on "true" or "apparent" K_La -- In an aerated, steady state respiring system, the rate of oxygen transfer per unit volume, W_f, will be equal to the rate of biological uptake per unit volume, R. It has been shown earlier that, for submerged aeration, the clean water oxygen transfer rate, W, can be adequately modelled in two ways; based on the "true" K_La, K_La^*:

$$W = K_La^*(C^* - C) \qquad (36)$$

and based on the "apparent" K_La:

$$W = K_La(C^*_\infty - C) \qquad (37)$$

For dirty water field applications, these expressions, respectively, become:

$$W_f = K_La^*_f(C^*_f - C) \qquad (38)$$

and:

$$W_f = K_La_f(C^*_{\infty f} - C) \qquad (39)$$

The field transfer coefficients and saturation values can be related to the clean water values through the use of the adjustment factors, α, β, θ, τ, and Ω.

$$W_f = K_L a^*_{20} \alpha^* \theta^{*(T-20)} (\Omega \tau \beta \; C^*_{20} - C) \tag{40}$$

and:

$$W_f = K_L a_{20} \; \alpha \theta^{(T-20)} (\Omega \tau \beta \; C^*_{\infty 20} - C) \tag{41}$$

Note that Equations 36 and 38, based on $K_L a^*$, contain a driving force based on C^*, the actual effective saturation concentration corresponding to the actual gas side oxygen depletion. On the other hand, Equations 39 and 41, based on $K_L a$, incorporate a driving force based on C^*_∞, the effective saturation concentration attained when the inlet and exit gas oxygen fractions are equal. It is generally more convenient to base the driving force on C^*_∞ because it can be determined from unsteady state data. This parameter can be incorporated into Equation 40 by defining the dimensionless exit gas depletion factor, F, so that, at field conditions:

$$F = \frac{C^*{}_f}{C^*_{\infty f}} \tag{42}$$

giving:

$$W_f = K_L a^*_{20} \; \alpha^* \theta^{*(T-20)} (\Omega \tau \beta \; F C^*_\infty - C) \tag{43}$$

The exit gas depletion factor is evaluated based on the relationship between C^* and C^*_∞ employed in the determination of $K_L a$. Substitution of $R = \frac{dC}{dt}$ into Equations 21, 22, and 23 yields:

$$F = \frac{C^*{}_f}{C^*_{\infty f}} = \left(1 - \frac{R}{2\phi_d C^*_\infty}\right) \tag{44}$$

Aeration design equations are frequently expressed in terms of the SOTR, defined as the rate of oxygen transfer in clean water at zero DO and a specified temperature, usually 20°C. Based on $K_L a^*$:

$$\text{SOTR} = K_L a^*_{20} \; F_o \; C^*_{\infty 20} \; V \tag{45}$$

where:

F_o = F evaluated at zero DO = $1 - \frac{OTE_o}{2}$ and based on K_La:

$$SOTR = K_La_{20}C^*_{\infty 20}\,V \tag{46}$$

The resulting design equations for the field oxygen transfer rate, OTR_f, are developed from Equations 41 and 43:

$$OTR_f = \frac{\alpha^*(SOTR)\theta^{*(T-20)}}{F_o\;C^*_{\infty 20}}(\tau\beta F C^*_{\infty 20} - C) \tag{47}$$

and:

$$OTR_f = \frac{\alpha(SOTR)\theta^{(T-20)}}{C^*_{\infty 20}}(\tau\beta C^*_{\infty 20} - C) \tag{48}$$

In applying these equations, it is essential that careful attention be given to the definition of the various terms. Each approach will predict a correct value for OTR_f. However, indiscriminate combinations of the two approaches can lead to gross errors. Also, it has been shown earlier in this report that application of the SOTR to a compartmentalized system requires that C be greater than the value that limits the biological uptake rate, R, in all regions.

Differences between "true" and "apparent" values of alpha and theta -- In the approach based upon the "true" K_La, K_La^*, the impact of gas side oxygen depletion must be considered both in the interpretation of unsteady state test data and in the field application. However, this approach has the advantage of dealing with a real volumetric mass transfer coefficient. Consequently, the alpha and theta factors are defined as ratios of mass transfer coefficients.

The "apparent" K_La approach is simpler in that the impact of gas side oxygen depletion is automatically reflected in the estimate of K_La. A drawback of this approach is that the alpha and theta factors are not represented as simple ratios of volumetric mass transfer coefficients. By combining Equation 25 with the definitions of α^* and α given in Equations 27 and 33, it can be shown that:

$$\frac{\alpha^*}{\alpha} = \frac{2\phi_d - K_La}{2\phi_d - \alpha\beta K_La} \tag{49}$$

Application of typical values of $\phi_d = 0.75\ \text{min}^{-1}$, $K_La = 0.15\ \text{min}^{-1}$, and typically low values of $\alpha = 0.5$ and $\beta = 0.9$ in Equation 49 indicates that the ratio α^*/α would be about 0.94, or that failure to distinguish between α^* and α could result in an error of 6 percent.

A similar development shows that the "true" and "apparent" values of theta are related by:

$$\left(\frac{\theta^*}{\theta}\right)^{(20-T)} = \frac{2\phi_{d20} - \theta^{(T-20)}\tau\ K_La_{20}}{2\phi_{d20} - K_La_{20}} \tag{50}$$

Again, application of typical values ($\phi = 0.75\ \text{min}^{-1}$, $K_La = 0.15\ \text{min}^{-1}$, $\tau = 1.1$, and $\phi = 1.02$) indicates that $(\theta^*/\theta)^5 = 1.0004$, or that failure to distinguish between the true and apparent values of θ could only account for 0.04 percent error when adjusting over 5°C. The net error introduced by failure to distinguish between "true" and apparent" values of both α and θ would, therefore, amount to 6 percent. However, even for a given sample of wastewater, it is difficult to measure α within an accuracy of 10 percent. Considering wastewater variability, the accuracy of a "design" value of α might be ±15 percent. Likewise, the uncertainty involved in values of θ can result in substantial errors apart from the failure to distinguish between θ^* and θ. Values of θ ranging from 1.020 to 1.030 are commonly employed[9,10] and, over 5°C, would lead to differences of about 5 percent in the prediction of field transfer rates.

Parameter Estimation

Fitting Equations to Data --

There are three immediate areas of concern when one is faced with the problem of fitting a mathematical model to a given set of data. The first is whether the proposed equation does in fact correctly model the system under study. The second is how to select the "best" estimates of the parameters in the proposed model. The third is to determine the precision of the computed parameter estimates. Each of these questions has been addressed by Brown[11] in the context of the analysis of unsteady state oxygen transfer test data.

Excellent introductory treatments of linear least squares theory and application can be found in the texts by Miller and Freund[12] and by Walpole and Myers.[13] More advanced treatments of linear and nonlinear least squares are presented in the texts by Draper and Smith,[14] Beck and Arnold,[15] and Bard.[16] A number of transformation schemes for performing weighted least squares analysis have been suggested by Davies.[17]

For a review of nonlinear estimation methods, including references and program sources, refer to Chapters 7 and 8 and Appendix D of the text by Beck and Arnold.[15] The list of nonlinear programs that follows is taken from Appendix D of Beck and Arnold.[15]

Nonlinear Estimation Programs

BARD	A nonlinear least squares program that uses the Gauss method (Ref. D3, page 218).
BSOLVE	A nonlinear least squares program that uses Marquardt's method (Ref. D3).
	NLIN IBM Share Program SD 3094 written by Marquardt and others. Written in Fortran IV for IBM 7040. Uses Marquardt's method with derivatives or finite difference approximations to solve weighted least squares problems.
NLINA	This is a program written at Michigan State University by J. V. Beck and available from him. It uses the sequential and Box-Kanemasu modifications of the Gauss method.
SSQMIN	This program uses the Powell procedure and is discussed in Ref. D3.

References (from Beck and Arnold)[15]

D1	Himmelblau, D. M., Process Analysis by Statistical Methods, John Wiley & Sons, Inc., New York City, 1970.
D2	Bard, Y., Nonlinear Parameter Estimation, Academic Press, Inc. New York City, 1974.
D3	Kuester, J. L. and Mize, J. H., Optimization Techniques with Fortran, McGraw-Hill Book Co., New York City, 1973.

In addition, the computer science and/or statistics departments at most major universities have general purpose nonlinear estimation programs available. One that is particularly well documented and suitable for the exponential method is NREG, available from MACC at the University of Wisconsin-Madison. Also, a nonlinear regression program at Purdue University (SPSS21) has been applied to fitting oxygen transfer data.[18]

A nonlinear regression program dedicated to Equation 3 has been developed by the Subgroup on Oxygen Transfer Modelling and Data Interpretation and is presented in Appendix A of this report. Such a program is attractive because it is much simpler in scope than the sophisticated general purpose routines available on large computers. The program is based on modifications of the method of Reed and Theriault.[19] This strategy has been used by Marotte,[20] Gilbert and Libbey,[3] and Kothandaraman[21] in the analysis of aeration data.

Comparison of Data Analysis Techniques --

A variety of graphical and numerical procedures have been proposed for the analysis of unsteady state oxygen transfer data. A general review of these procedures has been given by Brown.[11] They are conveniently grouped into three categories: the exponential, log deficit, and direct methods. The methods derive their name from the form of the equation used to fit the data. The basic oxygen transfer model can be expressed in three forms; first, the direct of differential form:

$$\frac{dC}{dt} = K_L a(C^*_\infty - C) \tag{1}$$

second, the log deficit form:

$$\ln(C^*_\infty - C) - \ln(C^*_\infty - C_0) = - K_L a\ t \tag{2}$$

and third, the exponential or integral form:

$$C = C^*_\infty - (C^*_\infty - C_0)\exp(- K_L a\ t) \tag{3}$$

Exponential method -- The exponential method fits Equation 3 to the experimental data. The values of DO concentration are used directly and Equation 3 is fit to the data using nonlinear squares procedures. Boyle et al.[22] use the technique of Marotte[20] and Marquardt[23] and Gilbert and Libby[3] the technique proposed by Reed and Theriault[19] for the analysis of first-order kinetic data. The main advantage of this method is that the computational procedure provides least squares estimates for all three parameters without any constraints placed on the data used (truncation) or on assumed values of the parameters. The parameter estimates are more precise than those obtained from the other procedures. For efficient calculations, however, the method requires the use of a computer or advanced scientific calculator.

Log deficit method -- The log deficit method fits Equation 2 to the experimental data. It has the advantage of being linear in K_La (allowing linear least squares to be used for parameter estimation) but requires that a value of C_∞^* be assumed, calculated, or measured to calculate the deficits. The estimate of K_La will be biased to the extent that C_∞^* is selected incorrectly. In the literature, the general concensus is that the measured value of C when the aeration test is allowed to proceed to equilibrium is the value of choice for C_∞^*.[2,3,4,5] Another disadvantage of the method is that the data may have to be truncated near saturation to avoid the problem of negative deficits, which cannot be handled logarithmically. Additional discussion of the log deficit method is presented early in this section.

Direct method -- The direct method fits Equation 1 to the experimental data. This method has the advantage of being linear in K_La and of not requiring that a value of C_∞^* be specified to do the least squares analysis. The main disadvantage of the direct method is that it magnifies the noise in the data. The process of approximating the rate of oxygen transfer, $\frac{dC}{dt}$, by taking differences between successive concentration values results in a variable that has substantially larger error than the error in C itself. Even if the original test data are smooth, the scatter in the direct method of analysis is noticeable.[2] This is especially disturbing if the concentration data are noisy[24] because the estimates of K_La are less precise than with other methods and because it may be necessary to discard substantial portions of the data at both high and low values of C to get a good fit.[25]

Experimental Design

According to Berthouex and Hunter,[26] parameter estimation is most efficient if care is taken in selecting the times at which observations of the dependent variable are made. For models of the type of Equation 3, it can be shown that the important observations times are zero, $1/K_La$, and infinity. These times correspond to the maximum sensitivity of C_0, K_La, and C_∞^*, respectively, to the data. Thus, an efficient experimental design should reflect these sensitivities. The regression analysis with Equation 3, therefore, should be based on a minimum of 10 to 15 data values. Approximately two-thirds of these values should be evenly distributed over the time period of $0/K_La$ to $2/K_La$ (or approximately 0 percent saturation to 86 percent saturation; see Table 1). The remaining one-third of the values should be evenly distributed over the time period $2/K_La$ to $4/K_La$ (or 86 percent saturation to 98 percent saturation). If substantial uncertainty exists concerning the anticipated value of K_La, the test should be conducted for as long a period of time as possible to insure a length of at least $4/K_La$.

Data Truncation and Model Adequacy

Truncation in the Vicinity of Equilibrium --

Boyle et al.[22] have shown that truncation increases the correlation between K_La and C^*_∞ and reduces the precision of the estimated K_La. The information in Table 3 obtained by truncating the data of Gilbert and Chen[2] at various increments of $1/K_La$ also demonstrates this effect. The log deficit methods require truncation to avoid negative deficits. Truncation is often necessary in the direct method because of the difficulty of estimating $\frac{dC}{dt}$ as the rate of transfer approaches zero. Although truncation is generally necessary with these methods (especially if the data are noisy), it is not statistically desirable. The exponential method does not require truncation.

Truncation at Low Concentrations --

In the analysis of unsteady state oxygen transfer data, the emphasis is usually placed on obtaining precise and accurate values of K_La and C^*_∞. This is the case because these parameters are used to compute the standard oxygen transfer rate, SOTR, which is an indicator of an aeration system's performance. As has been shown by Boyle et al.,[22] data at the beginning of the test ($C < 20$ percent of saturation) have negligible effect on the ability to estimate K_La and C^*_∞. Thus, it would seem that data in this vicinity are not important.

This is not strictly true, however. Data values in the low concentration range are important in determining whether Equation 3 is an adequate model to describe oxygen transfer. In the development of Equation 3, it was assumed that the constant C^*_∞ could be used in place of the time varying saturation value C^*. While this assumption is not unreasonable for many surface and subsurface aeration systems, it may not be valid in aeration systems where oxygen transfer is rapid and there is an appreciable gas side oxygen depletion. The effect of gas side depletion, with the resultant lowering of C^*,

TABLE 3. EFFECT OF DATA TRUNCATION OF THE PRECISION OF PARAMETER ESTIMATION DATA OF GILBERT AND CHEN[2] USING EQUATION 3

Time of Truncation	K_La Least Squares Estimate (hr^{-1})	K_La Standard Deviation (hr^{-1})	K_La Rel. Std. Deviation (%)	C^*_∞ Least Squares Estimate (mg/ℓ)	C^*_∞ Standard Deviation (mg/ℓ)	C^*_∞ Rel. Std. Deviation (%)	Correlation Between K_La and C^*_∞
$6/K_La$	12.05	0.11	0.9	10.39	0.01	0.1	-0.71
$5/K_La$	12.05	0.12	1.0	10.39	0.02	0.2	-0.75
$4/K_La$	12.07	0.16	1.4	10.38	0.03	0.3	-0.83
$3/K_La$	12.13	0.26	2.1	10.37	0.06	0.5	-0.90
$2/K_La$	12.32	0.54	4.3	10.30	0.15	1.4	-0.96
$1/K_La$	13.65	3.91	28.7	9.75	1.39	14.3	-0.99

is most pronounced at low concentration values. Thus, observations at low DO concentrations provide information for tests of model adequacy and should not be truncated arbitrarily. On the other hand, DO values at the beginning of the test may have to be discarded if a lingering effect of the deoxygenation technique is known to exist. It should be noted that Equation 3 has been found to adequately describe unsteady state oxygen transfer data from a great majority of aeration devices, both surface and subsurface, commonly employed in wastewater treatment operations.

Error Structure of Oxygen Transfer Data --

All three methods of data analysis have difficulties with the error structure of the dependent variable.[11] In the exponential method, the error in the DO concentration may decrease as the concentration increases. In the log deficit method, the error in the DO deficit increases as the deficit decreases. In the direct method, the overall errors in the oxygen transfer rate are high and the magnitude of the error increases as the transfer rate increases. These observations suggest that a weighted regression analysis is required to account for the nonconstant error distribution. The variable transformation strategies of Davies[17] have been applied[11] to a limited set of data.[2] The transformations employed appear to have improved the error structure of the dependent variable. However, the results also indicated that the least squares estimates and their precision were not markedly affected by the transformations.

EXAMPLE DATA ANALYSIS

The following example* illustrates the recommended method for analyzing clean water unsteady state oxygen transfer test data. Acceptable alternate methods are also illustrated.

Test Description

A clean water field test was conducted on a coarse bubble submerged aeration system installed in a 43-ft diameter circular tank. Test conditions and data are given below:

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*Test data supplied by Sanitaire, Water Pollution Control Corporation, Milwaukee, Wisconsin.

Average water temperature: 14.5°C
Local barometer: 28.88 in. Hg = 14.19 psi
Tank depth: 20.2 ft
Diffuser submergence: 18.2 ft
Air rate: 903.5 scfm (based on 1.00 atm., 20.0°C, and 0.0 percent relative humidity)
Tank Volume: 29,300 ft^3 = $8.298 \times 10^5 \ell$

For convenience of illustration, the data were obtained by averaging the DO concentrations recorded from four properly located probes. (Note: It is recommended that, in practice, data from individual sample or probe locations be analyzed separately and that the resulting values of K_La and C^*_∞ be averaged.) Each probe was equipped with a digital readout that recorded the DO concentration at 15-sec intervals over the 60-min test duration. Eighteen data values given in columns 1 and 2 of Table 4 were selected for analysis. The value of K_La was roughly estimated to be 0.09 min^{-1}, resulting in a value of $2/K_La$ of approximately 22 min. Roughly two-thirds of the data values (11 points) were chosen at uniform intervals over the first 22 min and the remaining seven data values were selected at uniform intervals over the period covered by $2/K_La$ to $5/K_La$ (22 min to 55 min). A plot of these data (Figure 3) indicates that no anomolous values are present and that low-range truncation is not necessary.

Recommended Parameter Estimation Method

These data were analyzed by the nonlinear least squares Fortran program described in Appendix A, with the following initial parameter estimates:

$C_o = 0.2$ mg/ℓ $\quad C^*_\infty = 11.4$ mg/ℓ $\quad K_La = 0.1\ min^{-1}$

The resulting best fit parameter estimates and standard deviations were:

Parameter	C_o	C^*_∞	K_La
Best fit estimate	1.12 mg/ℓ	11.43 mg/ℓ	0.0869 min^{-1}
Standard deviation	0.0377 mg/ℓ	0.0182 mg/ℓ	0.00064 min^{-1}

The DO concentrations predicted by the model are given in column 3 and the residuals are given in column 4 of Table 4. Although some "trending" is evident in the residuals, their values are small and the estimated error at 0.03 mg/ℓ is roughly equal to the experimental error involved in a single

TABLE 4. CLEAN WATER TEST DATA*

Time (min)	Measured DO (mg/ℓ)	Predicted DO (mg/ℓ)	Residual (mg/ℓ)
2.0	2.77	2.77	0.00
4.0	4.15	4.15	0.00
6.0	5.35	5.31	+0.04
8.0	6.25	6.29	-0.04
10.0	7.08	7.00	-0.03
12.0	7.80	7.80	0.00
14.0	8.34	8.37	-0.03
16.0	8.85	8.86	-0.01
18.0	9.28	9.27	+0.01
20.0	9.62	9.61	+0.01
22.0	9.93	9.90	+0.03
25.0	10.24	10.25	-0.01
30.0	10.70	10.67	+0.03
35.0	11.00	10.93	+0.07
40.0	11.14	11.11	+0.03
45.0	11.20	11.22	-0.02
50.0	11.25	11.29	-0.04
55.0	11.30	11.34	-0.04

*Residual sum of squares (RSS) = 0.01617 $(\text{mg}/\ell)^2$
Degrees of freedom (df) = 18 - 3 = 15

$$\text{Estimated error} = \left(\frac{\text{RSS}}{\text{df}}\right)^{0.5} = \left(\frac{0.01617}{15}\right)^{0.5} = 0.03 \text{ mg}/\ell$$

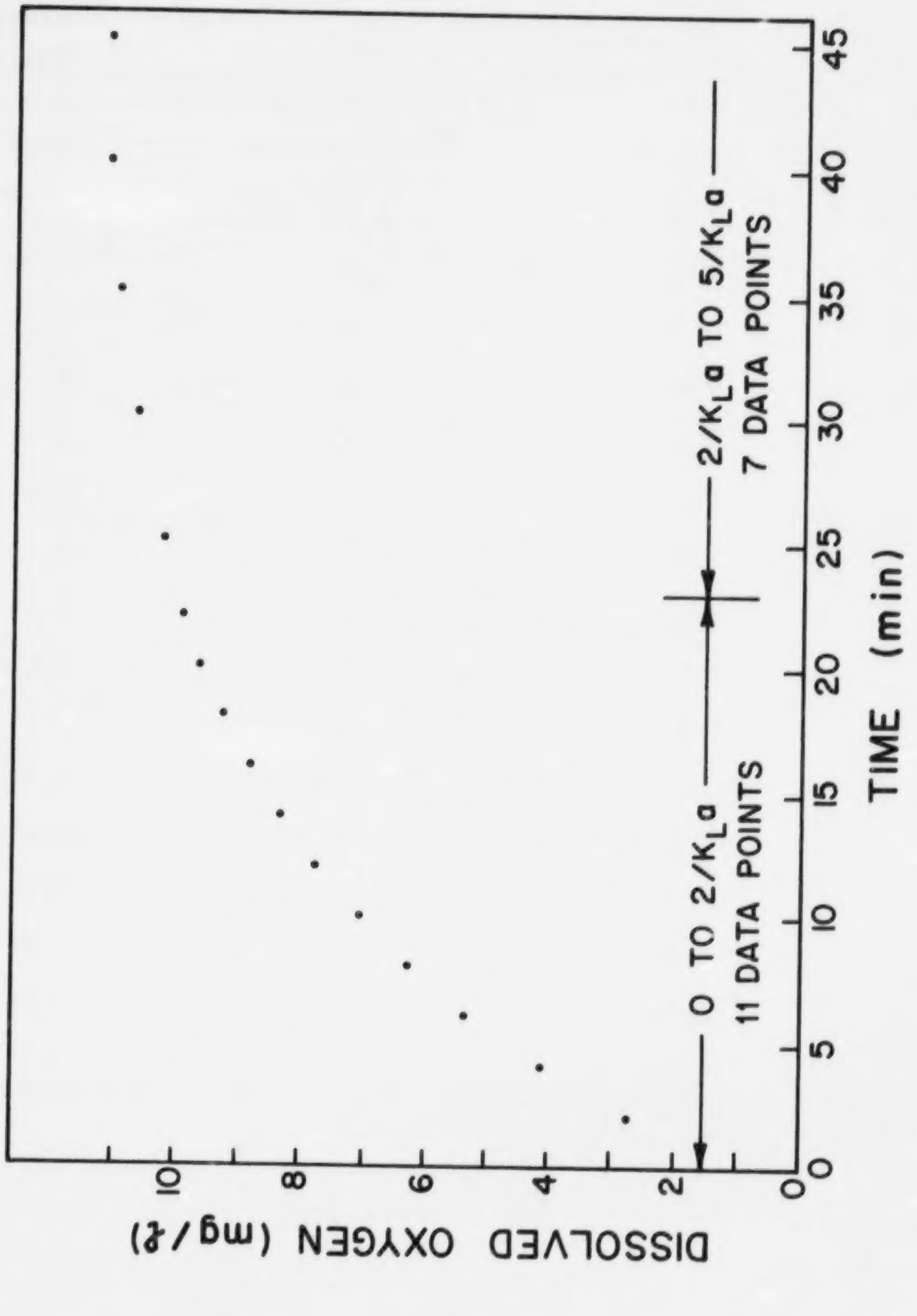

Figure 3. Clean water test data.

DO measurement. For example: If a single probe can measure DO to within 0.05 mg/ℓ, the error in the average of four probe values would be (0.05 mg/ℓ)/√4 = 0.025 mg/ℓ. On this basis, it can be concluded that the data are adequately described by the model.

The standard deviations of the parameter estimates are small and indicate excellent precision. For K_La, the standard deviation is only 0.73 percent of the best fit estimate. A suggested criterion for shop test acceptability is that the standard deviation of K_La be less than 5 percent of the best fit estimate.

Recommended Method: Calculation of SOTR Values Based on K_La

$$K_La_{20} = K_La_T\theta^{(20-T)}$$

$$K_La_{20} = 0.0869\ \text{min}^{-1}(1.024)^{(20-14.5)}$$

$$K_La_{20} = 0.0990\ \text{min}^{-1}$$

Determine effective saturation depth. Based on Henry's Law at 14.5°C, 1.00 atm., and 100 percent relative humidity:

$$\overline{H} = \frac{C_s}{Y_{air}(p_s - p_{vT})} = \frac{10.26\ \text{mg}/\ell}{0.21(14.696\ \text{psi} - 0.24\ \text{psi})}$$

$$\overline{H} = 3.380\ \frac{\text{mg}/\ell}{\text{psi}}$$

Effective saturation depth, d_e, at infinite time in an unsteady state test is defined by:

$$C^{\star}_{\infty T} = \overline{H}\ Y_{air}(p_b + \gamma_w d_e - p_{vT})$$

$$d_e = \frac{1}{\gamma_w}\left(\frac{C^{\star}_{\infty T}}{\overline{H}\ Y_{air}} - p_b + p_{vT}\right)$$

$$d_e = \frac{1}{0.433\ \text{psi/ft}}\left(\frac{11.43\ \text{mg}/\ell}{3.380\ \frac{\text{mg}/\ell}{\text{psi}}(0.21)} - 14.19\ \text{psi} + 0.24\ \text{psi}\right)$$

$$d_e = 4.97\ \text{ft}$$

Thus, the estimated C^*_∞ of 11.43 mg/ℓ corresponds to oxygen saturation at a depth of 24.6 percent of the tank depth.

Determine C^*_∞ at 20.0°C and a barometric pressure of 1.00 atm.:

$$C^*_{\infty 20} = C^*_{\infty T}\left(\frac{C^*_{s20}}{C^*_{sT}}\right)\left(\frac{p_s + \gamma_w d_e - p_{v20}}{p_b + \gamma_w d_e - p_{v20}}\right)$$

$$C^*_{\infty 20} = 11.43\ \text{mg}/\ell\left(\frac{9.17\ \text{mg}/\ell}{10.26\ \text{mg}/\ell}\right)\left(\frac{14.696\ \text{psi} + (0.433\ \text{psi/ft})(4.97\ \text{ft}) - 0.34\ \text{psi}}{14.19\ \text{psi} + (0.433\ \text{psi/ft})(4.97\ \text{ft}) - 0.34\ \text{psi}}\right)$$

$$C^*_{\infty 20} = 10.54\ \text{mg}/\ell$$

Finally, the SOTR is given by:

$$\begin{aligned}\text{SOTR} &= K_La_{20}C^*_{\infty 20}V\\ &= 0.0990\ \text{min}^{-1}(10.54\ \text{mg}/\ell)(8.298 \times 10^5\ell)\left(\frac{60\ \text{min/hr}}{453.6 \times 10^3\text{mg/lb}}\right)\end{aligned}$$

$$\text{SOTR} = 114.5\ \text{lb/hr}$$

Recommended Method: Application of Clean Water Test Data to Dirty Water Respiring Systems

The following calculations illustrate how the clean water SOTR determined above is related to an actual dirty water oxygen transfer rate, OTR_f, in a respiring system for given values of α, β, temperature, θ, DO concentration, barometric pressure, and geometry.

Given: $\alpha = 0.8$, $\beta = 0.9$, $C = 2$ mg/ℓ, $T = 15°C$, $p_b = 28.5$ in. Hg
= 14.30 psi, $\theta = 1.024$, submergence = 18.2 ft

Approach Based on "Apparent" K_La --

$$OTR_f = \left(\frac{\alpha(\text{SOTR})\theta^{(T-20)}}{C^*_{\infty 20}}\right)(\tau\beta\Omega\ C^*_{\infty 20} - C)$$

where:

$$\Omega = \frac{p_b + \gamma_w d_e - p_{v20}}{p_s + \gamma_w d_e - p_{v20}}$$

$$\Omega = \frac{14.30\ \text{psi} + (0.433\ \text{psi/ft})(4.97\ \text{ft}) - 0.34\ \text{psi}}{14.696\ \text{psi} + (0.433\ \text{psi/ft})(4.97\ \text{ft}) - 0.34\ \text{psi}}$$

$$\Omega = 0.976$$

$$\tau = \frac{C^*_{\infty T}}{C^*_{\infty 20}} = \frac{C^*_{sT}}{C^*_{s20}} = \frac{10.15\ \text{mg}/\ell}{9.17\ \text{mg}/\ell} = 1.1069$$

$$OTR_f = \left(\frac{0.8(114.5\ \text{lb/hr})(1.024^{-5})}{10.54\ \text{mg}/\ell}\right)\left(1.1069(0.9)(0.976)(10.54\ \text{mg}/\ell) - 2.0\ \text{mg}/\ell\right)$$

$$OTR_f = 63.7\ \text{lb/hr}$$

Alternate Method: Calculation of SOTR Value Based on K_La Corrected for Gas Side Oxygen Depletion

This approach recognizes that, because of oxygen depletion in the rising air stream, the "true" value of the volumetric mass transfer coefficient, K_La^*, is somewhat larger than the value of K_La. The calculation is straightforward but is complicated by the fact that the values of α and θ are usually given as ratios of K_La values and must be adjusted before applying them to K_La^* values.

First, the value of the oxygenation coefficient, ϕ_d, is calculated:

$$\phi_d = \frac{\left(\frac{M_O}{M_a}\right)\rho_a Q_a\ Y_{air}}{C^*_\infty\ V}$$

$$\phi_d = \frac{\frac{32}{28.97}(0.0753\ \text{lb/ft}^3)(903.5\ \text{ft}^3/\text{min})(0.21)}{11.43\ \text{mg}/\ell(10^{-3}\ \text{g/mg})(\frac{1}{453.6}\ \text{lb/g})(8.298 \times 10^5 \ell)}$$

$$\phi_d = 0.7547\ \text{min}^{-1} \quad \text{at} \quad 14.5°\text{C}$$

The oxygen transfer efficiency, OTE_o, at zero DO is given by:

$$OTE_o = \frac{K_La}{\phi_d} = \frac{0.0869\ \text{min}^{-1}}{0.7547\ \text{min}^{-1}} = 0.1151 \text{ or } 11.51 \text{ percent} \quad \text{at} \quad 14.5°\text{C}$$

The value of the "true" K_La, K_La^*, is calculated from the "apparent" K_La by:

$$K_La^* = \frac{K_La}{1 - \frac{K_La}{2\phi_d}} \qquad \text{or} \qquad K_La^* = \frac{K_La}{1 - \frac{OTE_o}{2}}$$

$$K_La^* = \frac{0.0869\ \text{min}^{-1}}{\left(1 - \frac{0.0869\ \text{min}^{-1}}{2(0.7547)\text{min}^{-1}}\right)} = 0.0922\ \text{min}^{-1} \quad \text{at} \quad 14.5°\text{C}$$

It can be shown by combining the definition of θ^* and θ with the relationship between K_La^* and K_La given above, that:

$$\left(\frac{\theta^*}{\theta}\right)^{(20-T)} = \tau\left(\frac{2\phi_{dT} - K_La_T}{2\tau\phi_{dT} - \theta^{(20-T)}K_La_T}\right)$$

$$= \frac{10.26\ \text{mg}/\ell}{9.17\ \text{mg}/\ell}\left(\frac{2(0.7547\ \text{min}^{-1}) - 0.0869\ \text{min}^{-1}}{2\left(\frac{10.26\ \text{mg}/\ell}{9.17\ \text{mg}/\ell}\right)(0.7547\ \text{min}^{-1}) - 1.024^{5.5}(0.0869\ \text{min}^{-1})}\right)$$

$$\left(\frac{\theta^*}{1.024}\right)^{5.5} = 1.0010$$

$$\theta^* = 1.0242$$

K_La^* is corrected to 20°C by:

$$K_La^*_{20} = K_La^*_T\theta^{*(20-T)}$$

$$K_La^*_{20} = 0.0922\ \text{min}^{-1}(1.0242)^{5.5} = 0.10516\ \text{min}^{-1}$$

Note that the difference between θ^* and θ is small. Greater differences will occur at larger values of OTE_o.

The SOTR value is given by:

$$\mathrm{SOTR} = K_L a^*_{20} F_o \; C^*_{\infty 20} V$$

where F_o is the exit gas depletion factor at zero DO and:

$$F_o = 1 - \frac{K_L a_{20}}{2\phi_{d20}} \qquad \text{or} \qquad F_o = 1 - \frac{\mathrm{OTE}_o}{2}$$

At 20°C:

$$\phi_{d20} = \phi_{d14.5}\left(\frac{C^*_{\infty 14.5}}{C^*_{\infty 20}}\right) = \phi_{d14.5}\left(\frac{C^*_{s14.5}}{C^*_{s20}}\right)$$

$$\phi_{d20} = 0.7547 \text{ min}^{-1} \left(\frac{10.26 \text{ mg}/\ell}{9.17 \text{ mg}/\ell}\right) = 0.8444 \text{ min}^{-1}$$

$$\mathrm{OTE}_o = \frac{K_L a_{20}}{\phi_{d20}} = \frac{0.0990 \text{ min}^{-1}}{0.8444 \text{ min}^{-1}} = 0.1172 \text{ or } 11.72 \text{ percent}$$

$$F_o = 1 - \frac{0.0990 \text{ min}^{-1}}{2(0.8444 \text{ min}^{-1})} = 0.9414$$

$$\mathrm{SOTR} = 0.10516 \text{ min}^{-1}(0.9414)(10.54 \text{ mg}/\ell)(8.298 \times 10^5 \ell)\left(\frac{60 \text{ min/hr}}{453.6 \times 10^3 \text{ mg/lb}}\right)$$

$$\mathrm{SOTR} = 114.5 \text{ lb/hr}$$

This is identical (within rounding error) to the SOTR determined directly from $K_L a$ (page 44).

Alternate Method: Application of Clean Water Test Data to Dirty Water Respiring Systems

Given: $\alpha = 0.8$, $\beta = 0.9$, $C = 2$ mg/ℓ, $T = 15°C$, $\theta = 1.024$, submergence = 18.2 ft

Approach Based on "True" K_La, K_La^* --

$$OTR_f = \left(\frac{\alpha^*(SOTR)\theta^{*(T-20)}}{F_o C^*_{\infty 20}}\right)(\tau\beta F\Omega C^*_{\infty 20} - C)$$

Here again, the values of α and θ are defined in terms of K_La ratios and must be adjusted before applying them as α^* and θ^* to K_La^* values. Combining the definitions of θ^* and θ with the relationship between K_La^* and K_La yields:

$$\left(\frac{\theta^*}{\theta}\right)^{(20-T)} = \frac{2\phi_{d20} - \theta^{(T-20)}\tau\, K_La_{20}}{2\phi_{d20} - K_La_{20}}$$

$$\left(\frac{\theta^*}{\theta}\right)^5 = \frac{2(0.8444\ \text{min}^{-1}) - 1.024^{-5}\left(\frac{10.15\ \text{mg}/\ell}{9.17\ \text{mg}/\ell}\right)(0.0990\ \text{min}^{-1})}{2(0.8444\ \text{min}^{-1}) - 0.0990\ \text{min}^{-1}}$$

$$\left(\frac{\theta^*}{\theta}\right)^5 = \frac{1.5915\ \text{min}^{-1}}{1.5898\ \text{min}^{-1}} = 1.0011$$

$$\theta^* = 1.0242$$

Note that the computing equation used here is equivalent to that given on page 46 except that it is based on 20°C values for convenience.

Combining the definitions of α^* and α with the relationship between K_La^* and K_La gives:

$$\frac{\alpha^*}{\alpha} = \frac{2\phi_d - K_La}{2\phi_d - \alpha\beta K_La}$$

Evaluating this equation at 20°C:

$$\frac{\alpha^*}{\alpha} = \frac{2(0.8444\ \text{min}^{-1}) - 0.0990\ \text{min}^{-1}}{2(0.8444\ \text{min}^{-1}) - 0.8(0.9)(0.0990\ \text{min}^{-1})}$$

$$\frac{\alpha^*}{\alpha} = 0.9829$$

$$\alpha^* = 0.9829(0.8) = 0.7863$$

The difference between α^* and α is small here. Greater differences will occur for systems with high values of OTE_o and low values of α.

$$F_o = 0.9414, \text{ from page 47}$$

The exit gas depletion factor under operating conditions, F, is evaluated by:

$$F = 1 - \frac{\alpha\theta^{(T-20)} K_L a_{20} (\tau\beta\Omega\ C^*_{\infty 20} - C)}{2\phi_{d20}\ C^*_{\infty 20}}$$

$$F = 1 - \frac{0.8(0.8882)(0.0990\ \text{min}^{-1})[1.1069(0.9)(0.976)(10.54\ \text{mg}/\ell) - 2\ \text{mg}/\ell]}{2(0.8444\ \text{min}^{-1})(10.54\ \text{mg}/\ell)}$$

$$F = 0.9674$$

Note that a trial and error procedure is avoided here by making use of the known value of $K_L a$. Finally, OTR_f, is evaluated as:

$$OTR_f = \left(\frac{\alpha^*(SOTR)\theta^{*(T-20)}}{F_o C^*_{\infty 20}}\right)(\tau\beta F\Omega C^*_{\infty 20} - C)$$

$$OTR_f = \left(\frac{0.7863(114.5\ \text{lb/hr})(0.8873)}{0.9414(10.54\ \text{mg}/\ell)}\right)[1.1069(0.9)(0.9674)(0.976)(10.54\ \text{mg}/\ell)$$

$$- 2\ \text{mg}/\ell]$$

$$OTR_f = 63.7\ \text{lb/hr}$$

which is equivalent within rounding error, to the result given on page 45.

Alternate Parameter Estimation Procedure: Best Fit Log Deficit Method

In cases where the lack of a suitable computing facility prevents application of the recommended nonlinear least squares method, acceptable results may be obtained by adapting the log deficit method to estimate both $K_L a$ and C^*_∞ by trial and error. This can be performed with the aid of a hand calculator programmed to do linear regression.

The model, expressed in linear form is:

$$\ln(C^*_\infty - C) = \ln(C^*_\infty - C_0) + K_La\ t_0 - K_La\ t$$

This equation is fit to the test data by performing a linear regression of $\ln(C^*_\infty - C)$ versus time. The value of C^*_∞ is estimated by trial and error, the best estimate being the value giving the minimum residual sum of squares. The best estimate of K_La is determined from the linear regression based on the best estimate of C^*_∞.

The data should be plotted and examined for anomalous values. If necessary, values less than 20 percent of C^*_∞ may be truncated at the low end. Top end truncation is necessary to avoid taking logs of negative numbers, and it is recommended that values within 0.3 mg/ℓ of C^*_∞ be eliminated. The data points should be spaced as previously recommended, with the highest DO concentration being at least 95 percent of C^*_∞.

This method is illustrated by application to the first 14 data values given in Table 4. Calculations for trial values of C^*_∞ corresponding to 11.50 and 11.55 mg/ℓ are presented in Table 5. The relationship between the residual sum of squares and trial values of C^*_∞ (Figure 4) indicates that the best estimate of C^*_∞ is well defined at a value of 11.55 mg/ℓ. Using this value for C^*_∞, the individual data points along with the linear least squares line of best fit were plotted (Figure 5).

The resulting parameter estimates are:

$$C^*_{\infty 14.5} = 11.55 \text{ mg/}\ell$$

$$K_La_{14.5} = 0.0835 \text{ min}^{-1}$$

Following the method outlined on page 47, the SOTR is evaluated as 111.3 lb/hr, roughly 3 percent lower than the 114.5 lb/hr based on the nonlinear least squares procedure. This difference is caused by

1. the logarithmic transformation required for the linear regression and
2. the elimination of four data points near C^*_∞ in the Best Fit Log Deficit Method.

TABLE 5. APPLICATION OF BEST FIT LOG DEFICIT METHOD

Time (min)	Measured DO (mg/ℓ)	ln(11.50 - C)		ln(11.55 - C)	
		Measured	Predicted	Measured	Predicted
2.0	2.77	2.167	2.171	2.172	2.165
4.0	4.15	1.995	2.000	2.001	1.998
6.0	5.35	1.816	1.828	1.825	1.831
8.0	6.25	1.658	1.656	1.668	1.664
10.0	7.08	1.486	1.485	1.497	1.497
12.0	7.80	1.308	1.313	1.322	1.330
14.0	8.34	1.151	1.142	1.166	1.163
16.0	8.85	0.975	0.970	0.993	0.996
18.9	9.28	0.798	0.798	0.820	0.829
20.0	9.93	0.451	0.455	0.482	0.495
25.0	10.24	0.231	0.198	0.270	0.245
30.0	10.70	-0.223	-0.231	-0.163	-0.172
35.0	11.00	-0.693	-0.660	-0.598	-0.590

	ln(11.50 - C)	ln(11.55 - C)
Covariance	-7.683684	-7.474990
Correlation coefficient	-0.9998587	-0.9999277
$K_L a$(min^{-1})	0.085802	0.083472
Residual sum of squares $(mg/\ell)^2$	2.622×10^{-3}	1.258×10^{-3}

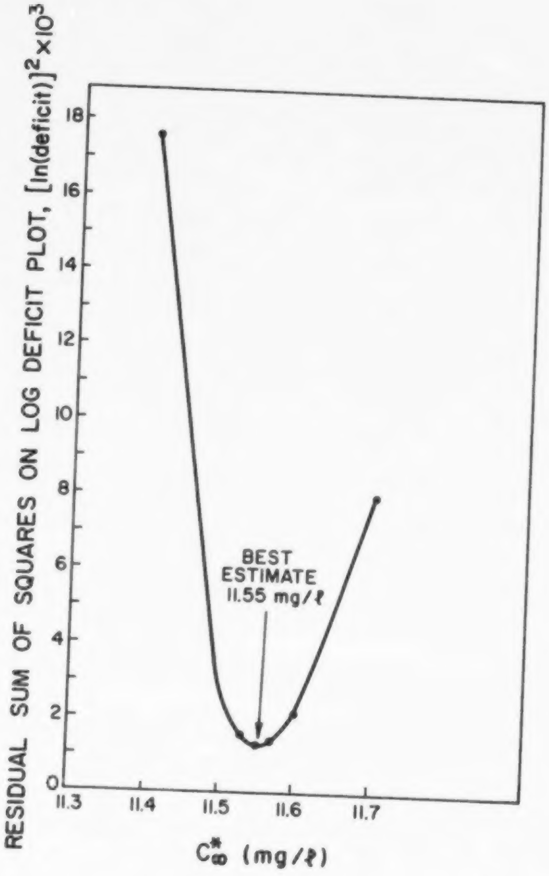

Figure 4. Relationship between estimated values of C^*_∞ and residual sum of squares.

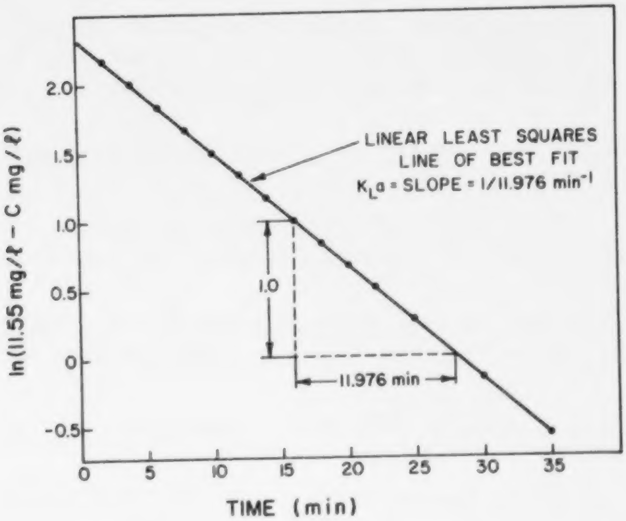

Figure 5. Log deficit plot based on $C^*_\infty = 11.55$ mg/ℓ and $K_La = 0.0835$ min^{-1}.

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SECTION 5

UNSTEADY STATE CLEAN WATER TEST

INTRODUCTION

The initial goal of the Subgroup on Unsteady State Clean Water Oxygen Transfer Testing was to develop an unsteady state clean water test procedure. After 2 yr of study and deliberation, it became clear that significant uncertainty exists in several areas of the test procedure that cannot be readily resolved or agreed upon. Some areas require additional study, and some uncertainties are due to varied experiences in extensive testing programs.

This section includes a Procedural Description subsection that can serve as a basis or guideline for preparing oxygen transfer testing specifications. It can also be used by owners, consultants, and manufacturers in evaluating oxygen transfer performance studies. The material presented in the Discussion subsection and in other areas of the project report can be utilized to complete the preparation of a testing and evaluation procedure. It is intended that this procedure be applicable to shop and field testing.

The procedure focuses on obtaining oxygen supply and transfer rate data. Detailed considerations of gas flow and power measurements, tank geometry and mixing, and modelling and data interpretation are presented in separate sections of the project report. Some requirements in these areas are included to provide a more complete procedural description and indicate where these topics are incorporated into the procedure.

To reach a reasonable degree of consensus, various options, alternative methods, and ranges of numerical criteria were cited, e.g., alternative dissolved oxygen (DO) analyses and cobalt levels. In some cases, e.g., water chemistry, analytical requirements are cited without numerical limits. This indicates an area of concern, and numerical limits may be cited for these parameters in the future.

An alternative or supplemental "clean water plus detergent" procedure was included. This was done in recognition of European practice in an attempt to possibly resolve chemical interference uncertainties and to provide a test procedure that would demonstrate differences in performance of different types of aeration devices (clean water versus clean water plus detergent). It has also been noted that tests with detergent added may more closely simulate wastewater performance. There is limited experience with this test procedure in the United States at present. The procedure needs further development and experience, but is included for the practical reasons noted above.

Following the Procedural Description, a multi-component Discussion subsection is presented. Typical existing approaches of consultants and manufacturers and committee/organization procedures have been published by the Water Pollution Control Federation,[1] the American Public Health Association in Standard Methods,[2] and the Process Equipment Manufacturer's Association.[3] Outside the United States, Germany and Austria have also published testing procedures[4] and the Ontario Ministry of the Environment has developed a procedure for mechanical aerator testing.[5]

Recommendations for additional study and procedural development are cited. A selected reference listing of publications is also presented.

PROCEDURAL DESCRIPTION

Advance Preparations and Responsibilities

Where field testing will be conducted, the engineer-owner-manufacturer (EOM) representatives should exchange information to assure that proper test conditions will exist for the oxygen transfer evaluation. The engineer-owner representatives should provide the manufacturer with detailed drawings and specifications of the tank or tank section in which the test will be conducted. Information on the water supply source and available water chemistry data should be provided. Water samples should be made available to the manufacturer for laboratory experiments regarding the chemical additions that will be made.

Once the installation of aeration equipment is completed, provision should be made for EOM representatives to inspect the installation to verify placement and testing conditions. Systems employing diffused air aeration should be tested to eliminate any leaks. Provisions for power and air flow measurements should be verified and modifications made as needed. It may be necessary to install equipment such as meters for power measurement, supplemental air piping, orifice plates, and manometers. This should be done in advance of the oxygen transfer test.

The owner and contractor should provide the equivalent of a public water supply, a ground water supply, or a treated surface water. Upon completion of the installation of the aeration equipment, the test tank should be cleaned prior to filling for testing. Once the tank is filled with the test water, chemical and biological, e.g., algae, contamination should be avoided. It may be necessary to dewater and re-fill the test tank during testing, and adequate pumping and discharge arrangements should be made.

Test Tank Geometry and Aerator Placement

It is difficult to describe a required geometry or placement for testing conducted in tanks other than the full-scale facility. Appropriate configurations for a particular application should simulate the field conditions as closely as possible. Water depths should be similar if not identical, and interferences due to wall effects and any extraneous piping or other materials in the tank should be minimized. The density of aerator placement, air flow per unit volume or area, and power input per unit volume are examples of parameters that can be used to assist in making comparative evaluations.

Consideration should be given to utilization of shop testing or testing of tank sections when full-scale facilities are very large, e.g., in excess of 1 mil gal. Considerations of distribution of deoxygenation chemicals and reasonable sampling requirements are criteria that can be considered in making the judgement.

Some specific requirements for aerator placement and tank geometry are described in the section on Geometry, Scale-Up, and Mixing. Minimum dimensions for diffused aeration test tanks are cited. Testing of multiple mechanical aerators is also described.

Air Flow Rate and Power Evaluations

Diffused aeration --

The air flow rate must be accurately and precisely determined using accepted procedures. Two recommended references for procedural assistance are Spink, L. K., Principles and Practices of Flow Meter Engineering, and Cusick, C. F., Flow Meter Engineering Handbook (see Section 9).

A full-scale air flow measurement system should be used with caution when testing in portions of the plant capacity. The precision or accuracy of the measurement device may not be adequate for test flow rates. Estimating air flow rates to part of the plant by volumetric or area served ratios could be used as a check but not for the primary air flow test information.

Where flow measurement equipment must be provided, calibrated orifice plate systems, venturi tube systems, and pitot traversing methods, e.g., the Annubar method, are recommended procedures. A precision of ± 5 percent is recommended. It is desirable to provide a back-up or supplemental measurement system as a check.

The air flow measurement system should be installed to avoid any potential pulsation effects from blowers. EOM representatives should establish an allowable variation in air flow rate during a specific test run.

Data that should be obtained to relate the measured air flow to standard conditions include in-line pressure and temperature, barometric pressure, ambient temperature, and relative humidity. Standard conditions for air flow are defined as 68°F (20°C), 14.70 psia (1 atm.), and 36 percent relative humidity.

When diffused aeration performance is based on power, required pressure measurements should be made to enable the calculation of the power required. Adiabatic and polytropic compression formulae can be used to make the calculation. Blower power measurements may be used if the total air supplied is employed in the testing.

Mechanical aeration --

The power requirements for the oxygen transfer performance test should be determined by procedures approved by EOM representatives. It is recommended that recording polyphase watt meters be utilized to determine the total power input of all aeration equipment. The watt meters should have a high degree of accuracy and be capable of monitoring 10 cycles/sec peaks. Strain gages and/or torque pickups may also be used to determine power requirements.

The equipment should be installed to minimize the measurement of power requirements other than those of the aeration equipment. EOM representatives should establish appropriate efficiencies of conversion between brake and line horsepower when needed.

EOM representatives should establish allowable liquid level variations during a test run.

Detailed discussions of air flow measurement and power measurement are presented in Sections 9 and 10, respectively.

Initial Water Quality

The initial test water should be equivalent to a public water supply, either a ground water source or a treated surface water supply. (A discussion of the relationship of Drinking Water Standards water quality to that for oxygen transfer testing is presented in the following Discussion subsection.) It is desirable that the water temperature be near 20°C. The temperature should be in the 10 to 30°C range. Testing at low temperatures will result in uncertainties of chemical reactions, especially in the deoxygenation process. Testing outside the range may be necessary in some field conditions and can be conducted with the approval of the EOM representatives. The recommended temperature correction value (theta) is 1.024. (A discussion of the variability of theta correction values is presented in Section 6.) The test water temperature should not change more than 2°C during a reaeration period.

Various physical and chemical constituents have been cited as interfering with or affecting the unsteady state test and/or the analysis of DO by the Winkler or membrane probe procedures. Prior to starting the testing program, a representative sample of the water to be used in the test tank should be analyzed for total dissolved solids (TDS), alkalinity, sulfate, iron, manganese, residual chlorine, pH, total organic carbon or chemical oxygen demand, cobalt, surfactant, and temperature.

EOM representatives should review these results to determine areas of potential effect on the testing program. Procedural criteria regarding limiting TDS or sulfate concentrations, pH effects, cobalt levels, interferences with Winkler or membrane DO testing, and interferences with the oxygen transfer rate should be established.

The initial water chemistry may indicate a need for modifying a limiting

TDS level, adjusting pH, using a blank in Winkler testing, stripping chlorine initially, or other changes in the testing criteria. The analysis would also provide a baseline for comparison with the water quality after chemical additions during deoxygenation.

Normally, no modifications of test water quality are made for "clean water only" testing. However, it may be that, due to a particular set of field conditions, a surface water may have to be treated. Demonstrated oxygen transfer rate effects due to water chemistry differences between the field conditions and the prior test data used to predict the field performance may be considered in agreeing upon any water quality modifications.

An alternate procedure involving the addition of anionic detergents is described at the end of the Procedural Description subsection. Where this testing method is used, initial surface tension measurements should also be considered.

Deoxygenation Chemicals

Nitrogen stripping of the oxygen in the test water is one alternative deoxygenation method. It is a widely-used laboratory and pilot plant procedure, but it is not normally specified in full-scale or field testing. Some concern exists regarding the effect of nitrogen concentration during the early portion of the reaeration period and the practicality of nitrogen stripping on a large scale.

Technical grade sodium sulfite (Na_2SO_3) is the recommended chemical for deoxygenation. The sulfite should be essentially cobalt free and contain no impurities that would alter the oxygen transfer rate analysis. Sulfite, with cobalt present, could be used where a range of cobalt concentrations are permitted and the limiting cobalt concentration is not exceeded.

The sulfite should be evaluated for impurities and potential interference in oxygen uptake evaluations. This can be done by chemical analysis of the supplied chemical and by comparative laboratory oxygen transfer rate analysis. Oxygen transfer rates using the supplied technical grade sulfite can be compared against analytical grade sulfite deoxygenation and nitrogen stripping deoxygenation methods. (A typical procedure is described in the Discussion subsection.)

Sodium sulfite is normally added in solution or slurry form. It is preferred that the sulfite be essentially dissolved in a separate mixing tank prior to its addition to the test tank. Saturated solutions contain 2.23 lb/gal at 20°C and 3.00 lb/gal at 30°C.

The sulfite deoxygenation reaction is catalyzed by cobalt. The cobalt source utilized should be cobalt chloride or cobalt sulfate, reagent grade. The cobalt should be dissolved prior to its addition to the test tank. Caution should be observed in obtaining complete solution of the cobalt when it is added in the sulfate form.

System Stability

The volume of water under aeration should be held constant for the test series unless it must be changed to meet different load conditions for a mechanical aerator. It may be necessary to set an allowable liquid level tolerance during a run.

The aeration system should be operated to achieve steady state conditions prior to starting the oxygen transfer evaluation. The hydraulic mixing regime should be established in the test tank for each test condition prior to deoxygenation. A steady power draw has been used to determine steady state for mechanical aerators. Some aerators require 30 to 40 min to achieve steady state.

For diffused air systems, water must be displaced from the aeration system prior to beginning the test. Steady manometer readings for orifice flow measurements and consistent air flow rate measurements for other flow measurement devices are indicative of this displacement. Lines with valves for purging water from the aeration system may be added for testing purposes.

Initial Run

It is recommended that the initial test run conducted for each filling of the test tank not be used as part of the compliance procedure. It should be used to verify test procedures including sulfite dispersion, sampling techniques, data recordings, etc. It would also provide an opportunity to check on chemical reactions, interferences, and DO probe calibrations and verify adequate residual cobalt, etc. It is frequently reported that chemical and testing uncertainties have occurred during the first test run.

Chemical Addition for Deoxygenation

The cobalt solution should be added prior to the beginning of oxygen transfer testing with the aeration system operating. The solution should be uniformly distributed into the test tank. Pumps and distribution systems may be required for large tanks. The cobalt solution should be dispersed throughout the tank by operating the aeration system for approximately 30 min. The cobalt catalyst should normally be added once for each test water.

It is recommended that a concentration of from 0.10 to 0.50 mg/ℓ of cobalt (as Co) be maintained in the test water. If a higher cobalt concentration is required due to low temperature (less than 10°C) testing or for other test conditions, analytical precautions due to potential Winkler titration interference should be observed.

Testing conditions, e.g., with detergent added, or oxygen transfer rate results that indicate an inadequate catalyst concentration may require supplemental additions of cobalt. Cobalt analysis should be conducted on the test water to assist in this evaluation.

The sodium sulfite solution is then added to deoxygenate the water. It is recommended that sodium sulfite be dissolved in mixing tanks outside the test tank and distributed uniformly and rapidly (in less than 3 to 4 min) into the tank. The use of pumps and flexible piping to distribute the solution across the tank surface is recommended. Testing conditions may prevent achieving a perfect sulfite solution prior to the addition. Addition in a slurry form is preferred over the direct addition in a crystal form. Extreme care should be exercised to assure adequate dispersion and dissolution in the test tank.

The theoretical requirement for deoxygenation is 7.88 mg/ℓ of sulfite (as Na_2SO_3) per 1.0 mg/ℓ DO concentration. Sulfite additions are made in excess of stoichiometric amounts. The amount of excess is dependent on the oxygen transfer rate of the aeration system and the size of the test tank. The amount of excess varies from 20 to 25 percent for high transfer rate systems. (See Discussion subsection for typical calculation.)

Sufficient sulfite solution should be added to depress the DO level below 0.50 mg/ℓ at all sample points. It should be noted that consistent repetitive testing results have been observed where the DO concentration has reached zero at all sample points and remained at zero for at least 2 min. Results from the initial test run can be used to help establish the proper quantity to be added.

Water Quality Monitoring During Testing

The test water quality should be reported for all testing programs. The initial water quality analysis cited earlier will provide a base water chemistry. The following parameters should be evaluated, but not necessarily for each run: iron, manganese, residual chlorine, surfactant, and TOC or COD. This analysis is related to potential interferences that may result from multiple sulfite additions and/or contamination from adjacent operations at a field test site.

The following parameters should be evaluated for each run: temperature, TDS, cobalt, and pH. An analysis should also be performed for unreacted sulfite, especially where non-uniform oxygen response data are noted during a run. Unreacted sulfite could be present due to inadequate dispersion or dissolution, inadequate cobalt concentration, and/or low temperature (say less than 10°C) reaction limitations. The sulfite ion concentration may be determined analytically. In addition, multiple samples may be obtained and analyzed at constant temperature to determine if there was a DO depletion with respect to time in the samples. A significant DO depletion would indicate the presence of unreacted sulfite in the test water at the time of sampling.

The cobalt concentration normally should not change during testing. Slight decreases have been observed in some testing. If the concentration falls below 0.10 mg/ℓ, additional cobalt may be needed to assure adequate oxidation of the sodium sulfite solution.

It has been reported that high TDS levels, in the 1500 to 2000 mg/ℓ range, have affected oxygen transfer measurements. It is recommended that each volume of water can be used for repetitive testing until the TDS concentration reaches 1500 mg/ℓ. Where high (say greater than 500 mg/ℓ) TDS levels are initially present, the limiting level may be raised. It is recommended here that the increase in TDS level be limited to approximately 1500 mg/ℓ. In these cases, repetitive testing at high and low levels should be conducted to evaluate any effects on the transfer rates.

In some testing with Winkler DO titrations, pH variations have affected the measured oxygen transfer rate. It has been recommended that the pH be controlled at 6.9. Other studies have not observed an effect of pH on oxygen transfer rates in the 6.5 to 9.5 range. A pH limit cannot be recommended at this time; however, the potential for uncertainty in results especially with Winkler titrations should be noted.

When the cobalt analysis cannot be readily made onsite in field testing, samples should be filtered (glass fiber paper) and analyzed at a later time. This is permissible if no water quality-related problems appear to be evident. The cobalt addition should be carefully and accurately made.

When detergent-added testing is conducted, analysis for anionic surfactant concentration and surface tension should be made for each run. Due to reported variations in concentrations with time, multiple sampling should be considered. Allowing a 20- to 30-min delay prior to deoxygenation may help to stabilize the concentrations.

Sampling

The number and location of sampling points will be dictated by the size of the test tank, aerator placement, and mixing pattern in the tank. The sampling locations should be selected to represent regions of variable DO and be geometrically distributed vertically and horizontally to best represent the tank contents. If the results of multiple sample points are to be analyzed by a simple average, the sample locations should be chosen so that each senses an equal portion of the tank volume.

It is recommended that a minimum of four sample points be used. One point should be at mid-depth, one at a shallow depth (greater than 2 ft below the surface), and one at a deep location (greater than 2 ft above the floor). It is suggested that sample points be at least 2 ft from walls and floors. They should be no closer to a surface than 10 percent of the depth or the length or width (smaller of the two dimensions) of the test tank. A greater number of sample points is desirable and needed for large complex aeration systems.

Two widely-used DO measurement techniques are recommended. The first procedure is the use of DO probes located at the sample points in the test tank. Data are obtained by directly reading DO meters and/or continuously recording the DO via a strip-chart or digital recorder. A submersible pump and/or Kemmerer sampler should be used to obtain discrete samples for calibration checks and water chemistry analysis.

The second sampling procedure consists of continuously pumping samples from the sampling points. All continuously-pumped sample lines should have a uniform short residence time between the pump inlet and sample discharge or measurement point. The pump inlet should be designed and placed to avoid air bubble entrainment. If 300-ml DO bottles are used for sampling, the flow rate should be adjusted to avoid air bubble entrainment and provide adequate bottle displacement rates. A bottle displacement time of from 6 to 10 sec is recommended.

With this system, the DO measurement may be made by a DO probe mounted in the sample line, by a DO probe mounted with a stirrer placed into the sample bottle, or by Winkler titration of the DO in the sample bottle. The in-line probe system must be observed continuously to prevent line clogging or damage to the membrane. If individual bottle samples are used, they must be carefully stored to prevent temperature change and degassing. They should be analyzed for DO as soon as possible.

If the pumped sample-individual bottle technique is used, it is recommended that a DO probe-meter system also be installed. This system would be used to help set sampling times, indicate when zero DO was reached during deoxygenation, and assist in determining the end of run by noting a stable maximum DO concentration. With continuously recorded DO data, deoxygenation and reaeration patterns could be studied to aid in evaluating the performance of the aeration system.

Oxygen Transfer Measurement

To provide adequate DO data for the transfer rate evaluation, a minimum of 10 to 15 samples or readings should be taken. Analysis of more than 20 data values usually does not result in a significant improvement in precision and may weaken the assumption of independence among the observations. Two-thirds of the values should be evenly distributed during the time period from $0/K_La$ to $2/K_La$. One-third of the values should be evenly distributed from $2/K_La$ to $4/K_La$. In cases of rapid transfer, the minimum time between observations should be 0.5 min. The interval is dependent on the type of aeration system and conditions of operation specified.

The in-situ DO probes should be fast-response probes equipped with 1.0-mil membranes and agitators. The probes should be carefully calibrated using test tank water and checked for linearity against Winkler titrated samples. The calibration should be verified prior to each test run. The probe readings can also be checked against discrete samples taken (Winkler titrated) during a test run for verification of the calibration.

DO probes require considerable care and attention to provide continuous reliable data. Back-up probes and meters should be available for replacement as needed. Standard Methods[2] reports an accuracy of ± 0.10 mg/ℓ and a precision of ± 0.05 mg/ℓ for probe analysis.

If the probes are placed in sample lines to measure the DO, they would not be equipped with agitators. The velocity of flow past the probe would be established and maintained to provide an accurate response from the probe. Similar care and calibration would be required for these measurements.

Probes used to measure the DO in 300-ml sample bottles should be equipped with a stirrer. Proper calibration procedures also apply in this case.

The modified Winkler DO analytical procedure of Standard Methods (Section 422)[2] should be followed for DO titrations. Some modifications of this procedure are under consideration by the Standard Methods Committee and should be noted for their potential use in oxygenation testing. It appears that phenyl arsine oxide (PAO) titrant will be approved. It is also likely that the British method for DO measurement will be approved. In this method, hypochlorite is added to oxidize interferences such as sulfite. Procedures using excess iodide to prevent the loss of iodine vapor at high DO concentrations should be considered if unexplained lower readings in the higher DO ranges are experienced.

Chemical interferences in Winkler DO titrations have been observed with some testing, especially when higher cobalt levels are used (in the 2.0 mg/ℓ range). An analytical procedure presented in the 11th edition of Standard Methods (1960) has been utilized to eliminate chemical effects. A sample of the test water is taken at the end of the test run. This sample is titrated directly without the addition of manganous sulfate solution, but with the addition of the alkali-iodide-azide reagent. This value, called a "blank", is subtracted from every DO measurement in the test tank to eliminate chemical interferences.

This correction procedure is not in the 14th edition of Standard Methods.[2] The "blank" has not been observed in several reports of oxygen transfer testing, especially where cobalt concentrations have been less than 0.5 mg/ℓ.

The Discussion subsection presents additional information regarding DO measurement using probes and Winkler titration.

Run Duration and DO Saturation

DO data should be obtained over as wide a range as possible. Truncation of data at DO levels less than 20 percent of C^*_∞ is allowable to avoid lingering effects of the deoxygenation technique. In no case should values of DO greater than 30 percent of C^*_∞ be truncated. Low DO values will be of use in assessing the model adequacy.

All test runs should be continued for a period of time approximately equal to 4 divided by the anticipated value of K_La. This normally is equivalent to continuing the run until the DO concentration is 98 percent of C^*_∞. It is desirable that each run be continued to the saturation DO level. As a minimum, one run should be extended for each testing condition (temperature, aerator operation, and geometry) to obtain a test saturation DO concentration.

The saturation concentration is normally reached when the run is extended for a period equal to $6/K_La$. The saturation concentration can be considered to be that concentration that remains constant for 15 min after a test has been continued for a time period equal to $5/K_La$.

It should be noted that this report (Section 4) recommends that values of C^*_∞ be estimated from the model. Measured and tabulated values of DO saturation concentrations should be used for comparative information and not as model parameters. A current table of DO saturation values is presented in the Discussion subsection for reference purposes.

Results and Interpretation

Aeration system performance should be evaluated on the basis of a minimum of three repetitive tests. The performance should be stated as an oxygen transfer rate in lb/hr or kg/hr at zero DO and 20°C for the specified physical conditions of placement, power, and/or air flow rate for the design.

The mean K_La value for the test tank, using all data, should be used to determine the mass transfer rate. The average mass transfer rate (lb/hr or kg/hr) should equal or exceed the stated performance requirement with a maximum variability of ± 5 percent of the mean for shop or factory-type testing. Variability of up to ± 10 percent may be permitted in field or full-scale testing. Two-thirds of the runs conducted for compliance testing should equal or exceed the required performance.

Values of K_La should be determined for each sampling point. The K_La values should not vary more than ± 10 percent from the mean value for each test run. It is recommended that 67 percent of the individual K_La values be within ± 10 percent for acceptable testing. Greater variations may be considered to be indicators of poor oxygen dispersion and/or analytical errors. Tests conducted in large tanks, e.g., in excess of 100,000 gal, may exhibit greater variations (say ± 15 percent).

The compartmentalized model presented in Section 4 on Modelling and Data Interpretation does not require that oxygen transfer occur throughout the tank volume, nor does it require that DO concentrations be uniform throughout the tank volume. For further discussion of this point, the reader is referred to Section 4.

Additional discussion of the interpretation of results, e.g., K_La variation and DO gradients, is presented in Sections 4 and 8.

Detergent Addition

Experience with this procedure is limited and varied. Additional information is presented in the Discussion subsection.

A strong solution of detergent, linear alkylate sulfonate (LAS) or household detergents, is prepared using hot water (80-90°C). The detergent solution is added in an amount to achieve an average concentration of approximately 5 mg/ℓ (measured as methylene blue active substance, MBAS) during a test run. An initial concentration of 7 mg/ℓ of detergent in the test water has been used. The detergent solution is added prior to the reaeration period and should be uniformly dispersed throughout the tank contents.

The detergent concentration (MBAS) in the test water should be analyzed at the beginning and end of the run and at several interim points to determine an average concentration for the run. Surface tension measurements at these times are also recommended.

The cobalt concentration should be checked to verify that adequate catalyst is present. It is suggested that a cobalt addition equivalent to 0.10 mg/ℓ in the test water be made for each run. Provision should be made to dispose of any foam that develops during the test. Some difficulty with detecting end points with the Winkler DO titration procedure have been noted. It is recommended that probes be used to monitor the DO concentration. The remaining test procedures are as noted in earlier sections.

Detergent testing results do not necessarily yield an actual performance alpha value for an aeration system. They may, however, provide oxygen transfer rate information to further describe and help predict the performance of the aeration system for municipal wastewater applications.

DISCUSSION OF PROCEDURAL COMPONENTS

The following subsection is keyed to the various Procedural Description components. Reports in the literature and approaches used in existing practice are cited. This is not intended to be a comprehensive literature review.

The Procedural Description presented in the first part of this section has been reviewed and revised by Subgroup and Subcommittee members. The information presented in this subsection will expand on some of the procedural components to assist individuals in developing oxygen transfer test procedures.

Advance Preparations and Responsibilities

This section focuses on testing for compliance with engineering specifications. Many reports by EOM's exist citing less than satisfactory test conditions. It is the intent of this subsection to encourage the exchange of information with the goal being to carefully delineate and agree upon the testing conditions that must be met and the responsibilities of each participant (engineer, owner, and contractor) in meeting the testing conditions.

Engineering firms have drafted specifications where the testing requirements are two paragraphs in length and others have been many pages in length. Black and Veatch,[6] CH_2M Hill,[7] and Bovay Engineers[8] are three examples of firms that prepare detailed testing descriptions and performance requirement statements.

As a minimum, the performance and precision requirements and type of testing, e.g., unsteady state with "clean water" or whatever procedure, should be stated. The detailed testing procedure could be described in the specifications, or provisions for establishing it sufficiently in advance of the testing date should be included in the specifications.

The responsibilities of each party should also be cited, e.g., provision of proper air flow and power measurements, provision of water supply, construction of tank sectioning or complete separation of a basin, special air piping installation, provision for laboratory space and utilities, etc.

Test Tank Geometry and Aerator Placement

Many consultants and owners require that final acceptance tests be conducted on the actual installation. In some cases, compliance testing is permitted under shop/factory conditions. There is concern on the one hand with obtaining proper measurements of air flow, power, and oxygen transfer rate (chemical handling and sampling problems due to size of test tank and field conditions) in field testing. In shop testing, the test procedures can generally be more precisely controlled; however, the question of properly simulating the geometry and aerator placement then becomes a major factor. Stukenberg and Wahbeh[9] have reported on problems with surface aerator testing under shop and field conditions. They concluded that "shop testing does not adequately predict the performance of aerators after they are installed in the field".

Bewtra and Nicholas[10] and Schmit et al.[11] have reported on the effect of tank dimensions and diffuser placement for diffused aeration systems. Rooney[12] has reported on the influence of tank geometry on aerator performance. He concluded that "basin geometry does affect the mixing regime established by a specific aeration device and thereby significantly influences its oxygen transfer rate".

Berk et al.[3] of the Wastewater Equipment Council, Process Equipment Manufacturers' Association (PEMA), recommended some criteria in 1972. They are:

Mechanical Aeration

Tank depth: 8 to 15 ft (as low as 3 ft for horizontal devices)
Power level: 0.04 to 0.30 hp/1000 gal

Note: Higher power levels and/or deeper basins will be permitted where the aeration device is tested for application in specific waste treatment systems that would operate under similar or identical conditions.

Diffused Aeration

Basin size: A rectangular tank with minimum length = 1.5 x depth and minimum tank width = 3 to 6 ft

Air supply: 12 to 45 scfm/1000 ft^3

Diffuser submergence: 8 to 14 ft

Note: Higher air supply and/or more diffuser submergence and/or smaller tank length and width will be permitted under test conditions where the aeration device is being tested for application in specific waste treatment systems that would operate under similar or identical conditions.

The Oxygen Transfer section of Standard Methods[2] notes that the value of K_La is affected by the type of aeration equipment and tank geometry. It is stated that "there are no universally accepted factors that can be applied to all aerators and test conditions to establish a reproducible K_La". It is observed that the power applied to a unit volume ratio is widely used to compare one system to another. An acceptable range of 0.05 to 0.20 hp/1000 gal is cited.

Section 8 of this report on Geometry, Scale-Up, and Mixing observes that horsepower per unit volume is an unreliable measure of solids suspension capability and further states that "the significance of relative power has meaning only when compared to similar aeration devices under similar conditions". (See Section 8 for additional discussion and guidelines regarding geometry and mixing.)

Air Flow Rate and Power Evaluations

The discussions of these components are included in Sections 9 and 10, respectively, of this report.

Initial Water Quality

Several investigators have reported on testing problems associated with using water sources other than a drinking water supply, e.g., river water, lake water, or final effluent. Chemical interferences with DO analytical procedures and oxygen transfer rates have been cited by several writers. Scaccia and Lee[13] have reported on a large number of constituents including dissolved gases, iron salts, organic matter, and several inorganic chemicals that interfere with DO measurement by probes and Winkler techniques. Kalinske et al.,[14] Landberg et al.,[15] and others have reported on the effect of high cobalt concentrations on oxygen transfer rate measurement using Winkler DO analysis. Naimee et al.[16] have reported on problems with high iron and manganese concentrations and variations in test results with pH levels. Other investigators have conducted oxygen transfer tests without observing adverse effects due to the presence of the interfering chemicals noted above. There is a considerable degree of uncertainty regarding the impact of chemical constituents in the test water. Additional information regarding water quality testing limits is presented later in this Discussion.

It would be desirable if a test or reference water quality could be specified. Typical wordings in some organizational procedural statements describe the test water as "clean tap water",[3] "fresh tap water",[2] and "quality of drinking water".[4] Other references include statements such as "clear water", potable water", and "clear tap water".

It has been suggested that "drinking water quality" be the reference water quality. No uniform definition of drinking water quality is recognized throughout the industry, and many public water supplies that meet Primary (Health) Standard water quality will vary widely in other chemical characteristics. Excerpts from EPA's Drinking Water Standards[17,18] and the World Health Organization (WHO)[19] along with selected water quality goals of the American Water Works Association (AWWA)[19] are presented in Table 6. Additional Primary (Health) Standards of EPA are presented in Table 7. Many U.S. waters do not meet the Secondary Standards.

Several modifications would be needed to adapt any of these standards as a reference water. Several numerical limits may need changing, e.g., sulfate, TDS, and other constituents added such as sulfite, chlorine, cobalt, etc. If a reference water quality was established, it could be reasonably achieved for factory, university, and research and development testing. Portable water treatment systems would be needed in some cases to modify the water quality

TABLE 6. EXCERPTS FROM DRINKING WATER STANDARDS

Constituent	EPA (1975)	WHO International (1971)		AWWA Goals (1968)
		Recommended	Acceptable	
Turbidity (TU)*	1	5	25	<0.1
Chlorinated-hydrocarbons*	(Several cited)			
Coliforms*	(Very low incidence)	(Very low incidence)		None
pH	6.5 to 8.5			
TDS (mg/ℓ)	500			
Chloride (mg/ℓ)	250	200	600	
Sulfate (mg/ℓ)	250	200	400	
Corrosivity	Non-corrosive			
Hardness (mg/ℓ as $CaCO_3$)				80 - 100
Iron (mg/ℓ)	0.3	0.1	1.0	<0.05
Manganese (mg/ℓ)	0.05	0.05	0.5	<0.01
Copper (mg/ℓ)	1	0.05	1.5	<0.2
Zinc (mg/ℓ)	5	5	15	<1.0
Foaming agents, MBAS (mg/ℓ)	0.5	0.2	1.0	
ABS (mg/ℓ)				<0.2
C-Cl extract (mg/ℓ)				<0.04
Odor (TON)	3			None
Color (Units)	15	5	50	<3

*Turbidity, chlorinated hydrocarbons, and coliforms are Primary (Health) Standards. The remaining EPA maximum contaminant levels are Secondary Standards. Specific pesticides are cited at low levels, and coliform presence is specified at a very low probability of occurrence.

TABLE 7. ADDITIONAL PRIMARY EPA DRINKING WATER STANDARDS

Constituent*	Maximum Contaminant Level (mg/ℓ)
Arsenic	0.05
Barium	1.0
Cadmium	0.010
Chromium	0.05
Lead	0.05
Mercury	0.002
Nitrate (as N)	10
Selenium	0.01
Silver	0.05
Fluoride (@ 68°F)	1.8

*Cobalt is not included as a Primary or Secondary Standard.

for testing. Some investigators have suggested modifications such as carbon treatment and pH adjustment in discussions of testing procedures.

As reported later in this Discussion, it has been suggested that a "detergent-added" procedure be used. One of the purposes of this procedural modification is to "overcome" the effects of the several interfering substances. This approach merits additional study.

Most procedural statements recommend testing close to 20°C whenever possible. Typical suggested acceptable temperature ranges are from 15 to 25°C. In northern climates, it may be necessary to test below 10°C. Caution regarding dissolution of chemicals and the effect on reaction rates is merited at low temperatures.

Stenstrom and the Alpha, Beta, and Temperature Corrections Subgroup of the ASCE Subcommittee on Oxygen Transfer Standards[20] have recommended that temperature corrections greater than 10°C be avoided if possible. They also have indicated that there is no consensus for a temperature correction factor. They recommend that a theta factor is more suitable. (See Section 6 for additional discussion.)

Deoxygenation Chemicals

Nitrogen stripping is an alternate procedure. This technique has been used in laboratory procedures by Scaccia and Lee[13] and others and has been used in shop testing by Houdaille Industries.[21] It has not been used in full-scale testing due to practical scale limitations and economics. Mandt[22] has reported that there may be some effect on early DO readings due to the residual nitrogen concentration from stripping. Early truncation, up to 20 percent of C_∞^*, may eliminate this effect.

There are several sources of sodium sulfite including Monsanto ("Santosite"), Stauffer, and Allied Chemical Companies. Nalco Chemical Company also supplies sodium sulfite as Nalco 19. Scaccia and Lee[13] and Naime et al.[16] have reported on "contaminants or impurities" in the sulfite that affect oxygen transfer rate measurements. Scaccia and Lee[13] report that technical grade sodium sulfite is produced in a batch-type operation with each batch being assigned a number. An assay of each batch is not available but is covered by a blanket analysis stating minimum or maximum quantities of expected chemical ingredients.

Sodium sulfite is frequently used as a boiler feed water deoxygenation chemical. Most sulfite can be obtained "cobalt free", so the cobalt concentration can be controlled by separate addition. Nalco 19, however, contains cobalt as a catalyst for deoxygenation. The cobalt concentration in the test water would increase with repetitive runs using this chemical.

A reagent grade sulfite could be used to avoid the impurities uncertainty. Its cost is from four to seven times greater than technical grade and its use in field or large-scale tests would be quite expensive. The price for analytical grade sulfite in 1977-78 was in the range of $0.85 to $1.00/lb, while the technical grade price was from $0.15 to $0.25/lb.

Scaccia and Lee[13] describe a laboratory screening test that could be used to evaluate any effects of the sulfite on oxygen transfer rate measurements. Comparative bench-scale reaeration tests could be conducted using nitrogen stripping and/or analytical grade sulfite for deoxygenation. One could also obtain samples of the water to be used in a field test and conduct evaluations of possible chemical effects due to water quality differences at the same time.

System Stability

Various references recommend aeration periods of from 20 to 30 min to achieve a steady state mixing condition in the test basin. Landbert et al.[15] observed that a 75-hp aerator requires 30 to 40 min to achieve a steady state hydraulic regime at the Lightnin test facility. They note that power readings and mixing velocities can be monitored to determine steady state. They observed that steady state power readings are achieved before steady state hydraulic conditions result. It was noted that each test condition (aerators and basin) will have its own steady state time constant.

Standard Methods[2] notes that the aeration device should be able to be operated at a constant power output for the duration of the test. Stukenberg and Wahbeh[9] have reported on difficulties and procedures in designing shop tests to simulate power levels of field-scale surface aerators.

Initial Run

Various investigators have reported that there have been uncertainties in the oxygen uptake response for the initial test on a new volume of water. It has been recommended that the initial run either be excluded from the runs utilized in analyzing for compliance or be made optional.

Boon[23] has suggested that the initial run be used to determine mixing by adding the sulfite and cobalt solutions at one point in a short time. Scaccia and Lee[13] recommend conditioning the test liquid by adding the sulfite solution in approximately the amount required to react with the DO in the liquid and continue aeration until saturation DO values are achieved. They state that this procedure allows for chemical stabilization of the test liquid so that results from an initial compliance test will be reproducible.

Chemical Addition for Deoxygenation

Cobalt is generally added in solution. The source is normally cobalt chloride although the sulfate or nitrate forms have also been used. Some concern has been expressed regarding difficulties of obtaining complete dissolution of cobalt sulfate. Cobalt is usually added once per tank of test water. Boon[23] has recommended that the cobalt concentration be analyzed prior to each run to be certain of its presence in adequate concentration. Additional cobalt would be added as needed to maintain an adequate catalyst concentration. Rooney[24] has also reported an occasional depletion in cobalt during the test and recommends that its concentration be verified by analysis.

Kalinske[25] has stated that "it has never been demonstrated that if 0.05 mg/ℓ of cobalt ion is added that there would be insufficient cobalt present for catalysis irrespective of how many tests are made in the water". Kalinske et al.[14] have recommended a cobalt concentration of 0.05 mg/ℓ. They also noted that with cobalt ion as low as 0.05 mg/ℓ, no unreacted sulfite was ever detected in the presence of DO, even with the water temperature below 5°C.

Berk[26] questions whether 0.5 mg/ℓ of cobalt is adequate, especially for testing in water temperatures below 10°C. He reported on testing difficulties using 0.5 mg/ℓ of cobalt that were corrected by raising the cobalt concentration to 2.0 mg/ℓ. Additional discussion of cobalt levels is presented under the following subheading, Water Quality During Testing.

Boon,[27] Scaccia and Lee,[13] and others have recommended that the sulfite be dissolved outside the test tank prior to its addition. Scaccia and Lee[13] recommend the use of mixing tanks (and heater systems where needed) to ensure complete solubilization. They note that undissolved sulfite transferred to the test tank may dissolve slowly causing an oxygen sink to be present during the reaeration phase of the test and result in an apparently lower K_La. Some investigators, e.g., McKinney[28] and Kayser,[4] have reported on successful use of dry addition of sodium sulfite.

The sulfite must be uniformly dispersed throughout the test tank to help ensure accurate reaeration results. Boon[27] states that rapid addition at a single point should be avoided or the concentration of DO may be variable during reaeration, even in a tank that is fairly uniformly mixed. Scaccia and Lee[13] recommend transferring the sulfite solution in a time period of approximately one-half to one basin turnover.

Sulfite additions are made in excess of the stoichiometric amount and are dependent on DO concentrations, oxygen transfer rates, and mixing intensity. Standard Methods[2] and WPCF Manual of Practice No. 5[1] suggest 0.8 lb/1000 gal, which represents a 22 percent excess. Berk et al.[3] suggest 1 lb/1000 gal, which represents a 50 percent excess. Boon[27] recommends 20 percent excess. Various references cite the necessity to go to at least twice the stoichiometric value to achieve a zero DO concentration. The theoretical stoichiometric requirement is 7.88 mg/ℓ of sulfite per 1.0 mg/ℓ DO concentration. The following data represent a typical array of sulfite quantities for different excess goals. The condition is a 100,000-gal test volume and an initial DO of 10.0 mg/ℓ.

Excess (%)	Sulfite (lb)
0	65.7
20	78.9
50	98.6
100	131.4
200	197.2

Stukenberg et al.[29] cite the importance of achieving zero DO prior to starting reaeration. They state that "if the basin is not deaerated completely, the results will be erratic and difficult to interpret". Kayser[4] reported that the West German and Austrian procedures require zero DO to be reached and maintained for 20 to 30 min. He states that this period of mixing at zero DO is of some importance when testing surface aerators. Boon[23] suggests that each in-situ probe be measuring about 0.1 to 1.0 mg/ℓ DO (within ± 10 percent of the mean) at the beginning of the reaeration period.

The requirement for reaching zero DO, if 20 percent C^*_∞ truncation of low DO levels is permitted, is questioned by some investigators. Another investigator indicated that a zero DO period of 2 min is acceptable if the sulfite is evenly distributed. It was suggested that in tanks with mechanical aerators, the DO should remain zero for the period required to establish constant velocities, turbulence, and energy uptake.

If in-situ probes are not used, the question has been raised how one could readily monitor the zero DO level simultaneously throughout the test facility. Additional Winkler DO analyses or the use of a probe-BOD bottle system would be required.

Water Quality During Testing

Testing experiences vary considerably regarding water quality limitations and effects. It appears that the greatest number of interferences or effects are associated with Winkler DO analytical procedures. Probe DO analysis avoids some of the analytical problems, but there are operational trade-off's regarding selection of the analytical procedure.

A wide range of cobalt concentrations have been used in testing. Low values, e.g., 0.05 mg/ℓ, have been recommended by Kalinske et al.[14] and others to avoid interference with Winkler DO testing. Stanton and Bradley,[30] concerned with the potential for inadequate catalyst concentration to oxidize the sulfite, recommend 2.0 mg/ℓ of cobalt. They utilize an analytical modification ("blank") to account for Winkler DO chemical effects. Landberg et al.[15] reported an increase in DO versus a control sample when the Na_2SO_3 concentration exceeded 500 mg/ℓ at a cobalt level of 5.0 mg/ℓ. Naimie and Burns[31,32] have reported that hydrogen peroxide was an interfering substance at pH's below 6.9 and a cobalt oxide precipitate was formed at pH's greater than 6.9. The buffering capacity and pH of the test water were determined to be the most critical water quality parameters regarding the magnitude of the interference. In general, water systems with higher pH values and substantial alkalinity caused interferences of unpredictable magnitude. Naimie et al.[16] concluded that an accurate quantitative prediction cannot be made of the magnitude of cobalt interference for various natural water systems with different water quality characteristics.

Scaccia and Lee[13] reported that cobalt concentrations in the range of 0.5 to 1.5 mg/ℓ had no effect on test results and that they normally use 0.5 mg/ℓ. Boon[27] reported that no effect on K_La was observed when testing with cobalt concentrations between 0.2 and 2.0 mg/ℓ. Paulson[33] in tests conducted on waters with alkalinities in the 150 to 250 mg/ℓ range has not observed any cobalt interferences with cobalt concentrations from 0.10 to 0.50 mg/ℓ.

Many investigators are recommending cobalt levels from 0.10 to 0.50 mg/ℓ. The West German and Austrian procedures as reported by Kayser[4] recommend 0.50 mg/ℓ. An EPA-sponsored clean water test project conducted by the Los Angeles County Sanitation Districts used 0.10 mg/ℓ of cobalt as reported by Yunt.[34] Values closer to 0.50 mg/ℓ are recommended for tests conducted at low temperatures (say less than 10°C). Multiple additions may be used with "detergent-added" testing due to the potential decrease in cobalt concentration as a result of formation of organic complexes and stripping.

TDS or sulfate concentrations have commonly been used as a basis for limiting the number of tests conducted on one volume of water. Landberg et al.[15] noted an effect on the Winkler DO determination at 1.0 mg/ℓ cobalt concentration and a Na_2SO_4 concentration of about 1200 mg/ℓ. Standard Methods[2] cites a decrease in solubility of oxygen of 0.009 mg/ℓ per 100 mg/ℓ of additional chloride at 20°C. For example, an increase of 1100 mg/ℓ of chloride would decrease the solubility 0.10 mg/ℓ.

Berk et al.[3] recommend a limiting Na_2SO_4 concentration of 1500 mg/ℓ (1010 mg/ℓ as SO_4). Scaccia and Lee[13] recommend 1000 mg/ℓ as SO_4. Zlokarnik[35] reports an increase in K_La when salt concentrations exceed 1500 to 2000 mg/ℓ. Kayser[4] reports that the German/Austrian procedural limit is a salt concentration of 2000 mg/ℓ.

Boon[36] reported that changes in the hardness of the water and small changes in concentrations of inorganic salts, including the sodium sulfate content, as a result of conducting several tests in the same water had little effect on test results. Boon[36] has also reported that up to ten tests have been conducted in the same water with little effect on the value of K_La determined by Winkler DO analysis or probes. Boon and his co-workers recommend a limiting TDS level of 1500 mg/ℓ. They also report no effect of alkalinity between 5 and 270 mg/ℓ on the test results. Other investigators have also reported that they did not observe any testing uncertainties with increasing TDS levels up to 2000 mg/ℓ.

Some firms, Black and Veatch,[6] Bovay,[8] and Sanitaire,[37] have recommended that a repetitive testing limit for water quality be based on the number of tests with the same volume of water. The range of allowable number of tests with the same water cited is from five to ten test runs. Envirex[38] and CH_2M Hill[7] permit the reuse of each volume of test water up to a limit of 1000 mg/ℓ of added TDS. It is suggested that repetitive runs be conducted at high and low TDS levels to check for possible significant K_La variations in testing programs. Naimie et al.[16] have reported on chemical interferences. They state that "data obtained from non-steady state clean water testing can be useful in comparison of aerator efficiencies only for test waters with very similar water quality characteristics". They observed that iron and manganese at concentrations of 2 mg/ℓ and probably other transitional elements substantially enhance (up to 100 percent) oxygen mass transfer during unsteady state clean water testing. They indicate that further work is needed at concentrations less that 2 mg/ℓ.

Naimie et al.[16] also report that values of K_La have increased as the hardness, pH, and sulfate content of the test water have increased. The effects were most pronounced, for a given test water, when five or more sulfite additions were introduced into the test basin.

If the Winkler DO titration method is used, Naimie et al.[16] recommend testing at a pH of 6.9 in a 0.01-molar phosphate buffered system with 2 mg/ℓ of cobalt, an iron concentration less than 0.3 mg/ℓ, and a manganese concentration less than 0.05 mg/ℓ.

Scaccia and Lee[13] have reported that a large number of chemicals interfere with oxygen transfer testing. No specific numerical limits other than for cobalt and sulfate (cited earlier) are recommended. Envirex[38] recommends stripping chlorine prior to commencing testing.

Some investigators have conducted tests in the pH range of 6.5 to 8.5 without observing significant effects of pH on K_La determinations.

It has been suggested that surface tension and anionic detergent analyses be conducted if "detergent-added" testing is conducted. Some question exists whether to use a static or dynamic surface tension measurement. McKeown and Okun[39] and Gilbert[40] have reported on surface tension measurements associated with surface active agents and oxygenation. Standard Methods[2] does not present a procedure; however, American Society for Testing Materials[41] has published a standard test method for surface tension of water. It has been reported by Gilbert [40] that the surface tension varies during a test run, but it appears to stabilize after approximately 20 min of aeration.

Anionic detergent concentrations can be measured by the Standard Methods[2] procedure as MBAS. Ewing et al.[42] have reported on the variations in LAS concentration with time during a test run.

The wide variation in the reported results of chemical interferences or lack of interferences demonstrates the need for further study to clarify many of the uncertainties. Section 6 also discusses the effects of chemical and other factors on oxygen transfer measurement.

Sampling

Section 4 of this report recommends that each sample point location sense an equal volume. Shell[43] states that to establish the variation in K_La at least four sampling points should be used. He indicates that the sampling points should be placed randomly in the basin avoiding the areas near the aeration issue and near the walls.

Shell[43] suggests the following criteria:

1. Do not place sample points in the plume or issue of the aeration device.
2. Do not place sample points any closer than 3 ft from the walls, 6 ft from the corners, or 2 ft from the basin floor and liquid surface.
3. Place one or more sampling points near the liquid inlet to the aerator.
4. Place sampling points at the one-third and two-thirds points in the basin both in relation to the diameter and depth. The diameter points should be on opposite sides of the basin.

The October 1978 draft of Section 208 (Oxygen Transfer) of Standard Methods[44] states that "for basins greater than 50,000 gal, locate six submersible sample pumps at various depths and at least at two places that divide the basin into approximately equal-volume sampling zones".

Berk et al.[3] in the 1972 PEMA procedure recommend the following approach:

> Two sampling locations shall be selected. One point should be fairly close to the aeration device, and the second point should be located near the tank periphery. Submersible pumps or siphons shall be installed at two operating depths at each sampling location. At the first location (close to the aeration device), pumps or siphons, shall be installed at mid-depth and three-quarters depth from the liquid surface. At the second location (close to the aeration tank periphery), pumps or siphons shall be installed at one-quarter depth and three-quarters depth from the liquid surface. This will give a total of four sampling stations for each test.

Stukenberg et al.[28] recommend a minimum of three sample points. They note that five to seven points are normal with more than ten points utilized for abnormal situations. Stukenberg et al.[29] illustrated recommended sample point locations for three aeration systems (Figure 6).

Section 4 of this report recommends 10 to 15 samples or DO readings with a maximum of 20 be taken for each location. A minimum time interval of 0.5 min is suggested for sample spacing with equal time intervals recommended in specific DO ranges as noted under the following subheading, Oxygen Transfer Measurement.

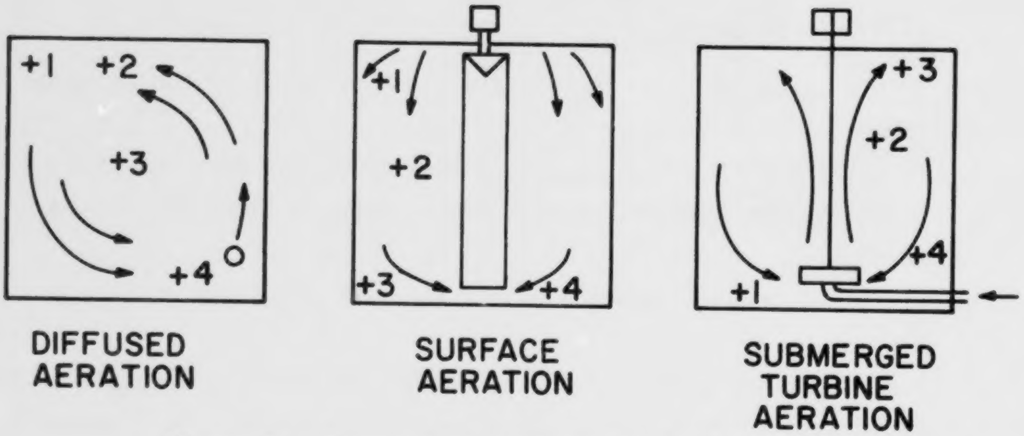

Figure 6. Recommended sample point locations.

Shell[43] recommends that timed samples be collected from each sample point. At least ten samples should be collected at each point for DO concentration analysis. Seven or eight of these samples should have an oxygen concentration between 10 and 90 percent of saturation. To achieve the appropriate time interval, the following expression can be used as a first estimate:

$$t = 100\overline{M}/OTR \qquad (51)$$

where:

t = sample time interval (min), t

$\overline{M}$ = test basin water weight (lb x 10^{-6}), m

OTR = estimated oxygen transfer rate (lb O_2/hr), m/t

Standard Methods[2] states that as the DO increases, samples are taken at 1- to 3-min intervals or one at approximately every 1.0 mg/ℓ increase in DO. The DO should be determined on six sets of samples between 10 and 80 percent saturation. Berk et al.[3] recommend a similar sampling quantity and spacing.

In-situ probes represent a widely-used sampling procedure. Boon,[26] Gilbert and Chen,[45] Paulson,[33] Envirex,[38] Marotte,[7] Sanitaire,[37] and Kayser[4] have utilized this procedure and recommend it as a sampling approach in their testing. This approach provides a continuous data source if the DO values are recorded. It provides a large number of data points if the meters are read directly.

Several references have been made to difficulties with reliable continuous operation of probes when operated in situ in test tanks. Shell[43] cites several problems with the use of probes as a sampling approach including damaged membranes, electronic malfunctions, and maintenance requirements. He also states that probes do not indicate a finite value of oxygen concentration. He further notes that "the indicated oxygen concentration is an average value over a period of time".

A second sampling approach is the use of either gravity flow or pumped samples. The samples can be analyzed by either DO method, Winkler or probe.

Standard Methods[2] states that the samples should be pumped at a rate that displaces the volume of each sample bottle at least three and preferably ten times between samples. The detention time between the pump and sample outlet should be limited to 5 to 10 sec. Sample pumps and lines of equal size and length should be used to minimize time differences among samples taken at a given time.

Samples should be collected in 300-ml BOD bottles at specific time intervals and sealed until analyzed. Sample lines should be handled carefully to avoid entraining air bubbles. Sampling should begin when the DO has just begun to rise from zero as indicated by a DO electrode located near the tank bottom and outer wall.

Shell[43] has recommended the following sampling procedure:

> The sampling procedure should be to place the sampling points (pumped or siphoned) in their proper locations in the aeration basin. Plastic tubing (about 1/4 in. diameter) should be connected from the sample point to a central collection point. At timed intervals, the plastic tubes are placed into the BOD bottles such that the ends of the tubes are within 1/2 in. of the bottle bottom.
>
> The rate of sample flow should be such that the bottle is filled within 5 sec. This means that the bottle contents will be replaced a minimum of three times in 15 sec.
>
> The length of the sample lines (for more than one sample point) is not critical if the retention time in the tube is less than 7.5 sec. If the retention time is greater than 7.5 sec, then all sample lines should be of the same length. To avoid possible data bias, the maximum sample line retention time should be 7.5 sec or less, if possible. Longer retention times may result in liquid temperature changes and possible additional aeration where air bubbles may be drawn into the sample line.

> To avoid the inclusion of air bubbles into the sample line, the sample point should be located away from areas of intense turbulence. The inlet to the sample point should be in a vertical plane with the opening at the top. The downward inlet velocity should be such that all air bubbles larger than 500 microns are excluded.

Conway and Kumke[46] continuously pumped a sample into a BOD bottle equipped with a magnetic stirrer. A probe was used to determine the DO concentration. Mixco[47] collects the pumped samples in BOD bottles and analyzes them with a DO probe.

Oxygen Transfer Measurement

The Winkler DO titration method has been widely used as a DO analytical procedure. Various oxidizing or reducing agents such as ferric and ferrous salts, residual chlorine, oxidizable sulfur compounds, nitrate and chromate, and readily oxidizable organics are examples of interfering substances in the Winkler titration procedure. Naimie et al.[16] reported on chemical interferences in oxygen transfer measurements. They have recommended pH control and limiting iron and manganese concentrations. They also noted that the effects of 2.0 mg/ℓ iron and manganese concentrations were not as pronounced with Winkler techniques as they were with DO probes. Kalinske et al.[14] have reported on cobalt interference resulting in high DO readings as the cobalt concentration increases. The limiting concentration cited for no interference was 0.05 mg/ℓ.

Scaccia and Lee[13] cited several substances (organic and inorganic) as causing interference in Winkler DO titrations. They note that *Standard Methods*[2] modifications will correct for ferrous and nitrite ion effects. They recommend the use of a "blank" to correct for or eliminate chemical interference effects. This "blank" approach has been recommended by Lakin[48] and Stanton and Bradley[30] to correct for chemical interferences when testing with cobalt concentrations of 2.0 mg/ℓ. The "blank" is obtained by titrating a sample directly without the addition of manganous sulfate solution, but with the addition of the alkali-iodide-azide reagent. This value is substracted from every DO measurement.

This "blank" procedure is not included in the 14th (1975) Edition of *Standard Methods*,[2] nor is it proposed in the 1979 Version of Dissolved Oxygen in Natural and Waste Waters (DOE-London).[49] There is some question as to the meaning or interpretation of the "blank". Gilbert and Chen[45] have reported that the "blank" value was always less than 0.2 mg/ℓ DO when using a 0.5 mg/ℓ cobalt concentration. They report that the "blank" represents interference caused by cobalt oxide reacting with iodide to form iodine. Stack[50] also reported that a cobalt precipitate that may be formed in testing causes the liberation of iodine upon acidification in the Winkler titration procedure. This interference results in an oxygen concentration value higher than the actual value. Stack suggests that the basic precaution should be to either use a low concentration of cobalt so that the interference is insignificant or if higher concentrations of cobalt are to be utilized to use DO probes.

Montgomery[51] and DOE-London[49] have reported that the loss of iodine vapor in titrations may result in lower DO values at the higher cobalt concentrations. This loss can be minimized by using a high iodide reagent (Modified Pomeroy-Kirschman-Alsterberg reagent). They note that this reagent is very viscous and may not be suitable for field use. Stack[50] also reported on the iodine volatility question. He recommended two actions to minimize the problem.

1. If Standard Method's[2] alkaline-iodide reagent No. 1 is to be utilized, add the manganous sulfate and alkaline-iodide reagents, carry the procedure through the flocculation stage, and cool the sample to a temperature in the 10-15°C range before adding the acid reagent. Titrate the sample with due consideration for the volatility of iodine.
2. Use Standard Method's[2] alkaline-iodine reagent No. 2 so that iodine is present as triiodide and iodine volatility is not a significant problem.

Samples for Winkler analysis should be analyzed for oxygen as soon as possible after sampling. The oxygen in the sample should be chemically fixed as soon as the sample is acquired. Mixco[47] and Conway and Kumke[46] recommend that care be taken to keep the DO samples at or below the temperature of the basin.

Standard Methods 14th Edition[2] and the DOE-London[49] procedures recommend the use of sodium thiosulfate as the titrant. The current WPCF Standard Methods Committee is recommending phenyl arsine oxide (PAO) as an equivalent alternate titrant. PAO has been shown to have a reasonably stable normality.

DO probes are used in many testing programs. In some cases, the probes provide primary data and in others they are used to control Winkler sampling procedures or provide supplemental information. Standard Methods[2] reports an accuracy of ± 0.10 mg/ℓ and a precision of ± 0.05 mg/ℓ for probe DO analysis.

Probes have been used successfully; however, many references cite concerns regarding special care, extensive calibration requirements, sensitivity, and response delays.

Naimie et al.[16] stated that DO probe results were affected to a substantial degree by concentrations of iron and manganese of 2.0 mg/ℓ in the test water. Scaccia and Lee[13] report that dissolved gases such as chlorine, H_2S, or SO_2 can interfere with DO measurements with membrane probes. Gilbert and Chen[45] reported on probe response time delay analysis. If the membrane probe equipment has a high membrane coefficient relative to the K_La being measured, no corrections are necessary.

Stack[52] reported that documents that best describe the appropriate procedures for use and calibration of probes are generally the literature provided by the manufacturers. He stated that the most important criterion is to have a good reference procedure. The three most commonly used are

1. a Winkler titration to determine the DO concentration in the calibration sample,
2. an oxygen-saturated sample, or
3. a water vapor-saturated air sample.

With suitable care in the Winkler titration, Stack[52] prefers the Winkler titration. A saturated water sample is acceptable as long as an adequate effort is made to saturate the sample and the table value for DO concentration is corrected for atmospheric pressure. In the water vapor-saturated air approach, it is important that the probe be at the air temperature and that the saturation value be corrected for atmospheric pressure.

Stack[50] has reported that a membrane probe cannot be calibrated in clean water and then placed in a contaminated water sample to read an oxygen concentration for use in the determination of a beta value. For successful application, the probe must be calibrated in the contaminated sample utilizing some reference technique such as Winkler titration.

Gilbert and Chen[45] have reported on the successful use of DO probes with the probes calibrated using saturated test water. The DO measurement was monitored using a multi-channel recording system.

Boon[27] uses DO probes in situ in his testing procedure. Boon[26] reports that to obtain accurate results, it is necessary to check frequently (at least daily) the reading of each probe at zero DO concentration and at 50 and 100 percent of the air-saturation equilibrium concentrations at the same water temperature used in the aeration tests. Calibration at 50 percent of saturation is normally achieved by aerating the water with an oxygen-nitrogen gas containing 10.5 percent O_2.

Conti[53] has reported that interference due to strong electrical fields has affected DO probe readings. Probes should be calibrated in the working environment in which they will be used in the testing program to avoid this interference.

Salzman[54] reported that due to probe response time and gas bubble attachment, in-situ use of probes is not recommended. Representative samples are pumped to sample bottles where measurements are made at steady state conditions. Probes are initially calibrated against saturated distilled water that is analyzed for DO by Winkler titration. During the reaeration phase, the test samples from a single point are analyzed by probe and Winkler titration to assure linearity.

Scaccia and Lee[13] describe an extensive detailed procedure for probe calibration and a linearity check using distilled water.

Boon[27] states that the thinnest membrane recommended by the manufacturer should be used to increase the sensitivity of the probe. He also reports that any protective shields should be removed to ensure a rapid flow of water past the membrane.

Kayser[4] has reported that the West German and Austrian procedures recommend the use of probes with agitators. Many investigators in the United States prefer 1.0-mil thickness membranes to minimize the likelihood of damage and utilize agitators to ensure adequate velocity past the membrane surface.

Ewing et al.[42] state that "there is some indication that more representative and reliable unsteady state test data may be obtained by multiple DO probes than by piped samples analyzed by Winkler or probes. The assumption of careful analysis and selection of the probe system, its application, and its calibration schedule is inherent in the above conclusion". Conway and

Kumke[46] concluded in their study that reliable oxygen analyzers make possible more rapid, accurate measurements of oxygen transfer.

It appears that the use of DO probes is a desirable procedure for obtaining continuous data, evaluating the beginning and ending performance of test runs, and avoiding some of the chemical interference questions associated with Winkler titrations.

Run Duration and DO Saturation

Several references have suggested terminating a test at from 70 to 80 percent of DO saturation. Boyle et al.[55] have cited the importance of obtaining data closer to saturation to minimize errors in estimating K_La. Recent procedural approaches are more frequently recommending that DO data be taken to 90 or 95 percent of the saturation DO. Boyle et al.[55] also noted that truncation of DO data up to 20 percent of DO saturation will not affect the precision of the estimate of K_La.

The truncation and run termination recommendations cited in the Procedural Description are based on the analysis by Baillod and Brown[56] (as repeated in Section 4 of this report). As noted, early truncation (20 percent) may avoid lingering effects of the deoxygenation technique. However, the need for early DO values is stressed for purposes of evaluating model adequacy.

Boon[27] recommends that test runs be continued to $6/K_La$ to reach the air saturation value. He uses DO values from 20 to 80 percent of the saturation value to calculate K_La values. Kayser[4] states that a test is finished when the DO does not increase by more that 0.1 mg/ℓ within 20 minutes. This DO reading is the saturation value.

Gilbert and Chen[45] recommend that the DO saturation concentration be determined experimentally for a given aerator type and system geometry. They determine the value by aerating the test tank until the DO reaches saturation and remains constant for at least 15 min. They report that truncation of an aeration test before reaching saturation can produce substantial error in estimates of K_La unless a precise value of C^*_∞ is available.

Standard Methods[2] DO saturation values are corrected for test conditions in the 1972 PEMA method by Berk et al.[3] and in the Standard Methods 1978 Draft Procedure.[44] Kalinske[25] specifies that saturation values for DO be determined from published tables, e.g., Standard Methods,[2] with appropriate corrections for salinity and pressure.

Stack[50] states that "where air-water interfaces are purposely dispersed in an oxygen transfer system, it is recommended that oxygen saturation be determined experimentally".

Section 4 of this report discusses truncation and DO saturation. It recommends that C^*_∞ values be estimated using the oxygen transfer model. Measured or adjusted tabular values would be used for comparative purposes and not as model parameters.

Hunter[57] has recommended the use of a table of saturation DO concentrations based on the 1973 International Oceanographic Tables (Table 8). According to Hunter, this table will probably be included in the 15th Edition of Standard Methods and is the most up-to-date and accurate information currently available. These values are utilized by DOE-London[49] in their solubility table. Five saturation DO values are listed below for comparative purposes.

Saturation DO Concentration (mg/ℓ)

Water Temperature (°C)	Table 8	14th Edition Standard Methods[2]
10	11.27	11.3
15	10.07	10.2
20	9.07	9.2
25	8.24	8.4
30	7.54	7.6

Results and Interpretation

Stukenberg[6] recommends that three replicate tests be run per set of aeration conditions. Rooney[24] states that confirmation of performance should be with at least three repeat tests with the results from all three to be within ± 5 percent of the average. He has suggested that two additional tests be required in order to discard one of the three original results.

Kayser[4] states that after two tests if single point values of mass transfer have a higher deviation than ± 5 percent of the average, this has to be explained (e.g., instrument failure) or a third test is required.

Conway and Kumke[46] reported that the variations of all but the extreme

TABLE 8. SOLUBILITY OF OXYGEN IN WATER EXPOSED TO WATER SATURATED AIR (mg/ℓ)

Water Temperature (°C)	Chloride Concentration in Water (mg/ℓ)				
	0	5,000	10,000	15,000	20,000
0	14.60	13.72	12.90	12.13	11.41
1	14.19	13.35	12.56	11.81	11.11
2	13.81	12.99	12.23	11.51	10.83
3	13.44	12.65	11.91	11.22	10.56
4	13.09	12.33	11.61	10.94	10.30
5	12.75	12.02	11.32	10.67	10.05
6	12.43	11.72	11.05	10.41	9.82
7	12.12	11.43	10.78	10.17	9.59
8	11.83	11.16	10.53	9.93	9.37
9	11.55	10.90	10.29	9.71	9.16
10	11.27	10.65	10.05	9.49	8.96
11	11.01	10.40	9.83	9.28	8.77
12	10.76	10.17	9.61	9.08	8.58
13	10.52	9.95	9.41	8.89	8.41
14	10.29	9.73	9.21	8.71	8.24
15	10.07	9.53	9.01	8.53	8.07
16	9.85	9.33	8.83	8.36	7.91
17	9.65	9.14	8.65	8.19	7.76
18	9.45	8.95	8.48	8.03	7.61
19	9.26	8.77	8.32	7.88	7.47
20	9.07	8.60	8.16	7.73	7.33
21	8.90	8.44	8.00	7.59	7.20
22	8.72	8.28	7.85	7.45	7.07
23	8.56	8.12	7.71	7.32	6.95
24	8.40	7.97	7.57	7.19	6.83
25	8.24	7.83	7.44	7.06	6.71
26	8.09	7.69	7.31	6.94	6.60
27	7.95	7.55	7.18	6.83	6.49
28	7.81	7.42	7.06	6.71	6.38
29	7.67	7.30	6.94	6.60	6.28
30	7.54	7.17	6.83	6.49	6.18
31	7.41	7.05	6.71	6.39	6.08
32	7.28	6.94	6.61	6.29	5.99
33	7.16	6.82	6.50	6.19	5.90
34	7.05	6.71	6.40	6.10	5.81
35	6.93	6.61	6.30	6.01	5.72
36	6.82	6.51	6.20	5.92	5.64
37	6.71	6.40	6.11	5.83	5.56
38	6.61	6.31	6.02	5.74	5.48
39	6.51	6.21	5.93	5.66	5.33
40	6.41	6.12	5.84	5.58	5.33

(continued on next page)

TABLE 8. (continued)

Water Temperature (°C)	Chloride Concentration in Water (mg/ℓ)				
	0	5,000	10,000	15,000	20,000
41	6.31	6.03	5.76	5.50	5.25
42	6.22	5.94	5.68	5.42	5.18
43	6.13	5.85	5.60	5.35	5.11
44	6.04	5.77	5.52	5.27	5.04
45	5.95	5.69	5.44	5.20	4.98
46	5.86	5.61	5.37	5.13	4.91
47	5.78	5.53	5.29	5.06	4.85
48	5.70	5.45	5.22	5.00	4.78
49	5.62	5.38	5.15	4.93	4.72
50	5.54	5.31	5.08	4.87	4.66

Ed. note: This table now appears in the 15th Edition of Standard Methods, APHA, Washington, D.C., 1980.

individual measurements from all clean water tests, both from series testing and multiple sampling points in the same basin, were less than 5 percent from the average values.

Boon[23] recommends an allowable variation in the mass transfer rate of ± 10 percent.

Various references cite a requirement for complete or adequate mixing for the unsteady state clean water test. The variations in point K_La values and DO gradients observed have frequently been cited as indicators of mixing.

It was shown in Section 4 that the basic model recommended in this report (Equations 1 to 3 of Modelling and Data Interpretation section) is in accordance with the analysis of both an ideal completely mixed system and an ideal compartmentalized system. The latter situation does not require that DO concentrations be uniform throughout the tank nor that oxygen transfer occur throughout the tank. However, an additional element of uncertainty is introduced in this situation by the assumption that the mean DO concentration of the accumulation zone equals the effective average DO concentration of the aeration zone. For further discussion of this point, the reader is referred to Section 4.

Shell[43] states that the basic mass transfer equation requires that mixing be complete, where complete mixing is defined as the continuous movement of all liquid in the basin. Shell[43] recommends that the variation in K_La values be used as a measure of mixing. He states that after reviewing the results of several hundred clean water tests, it was established that K_La values should not vary from one sample point to another more than ± 7.5 percent due to testing variations. If the K_La values vary more than ± 7.5 percent and no apparent test procedure problems are found, he states that the test results should be rejected on the basis of incomplete mixing.

Boon[27] reports that unsteady state testing utilizing the basic mass transfer equation assumes that the water being aerated is completely mixed and that at any time the concentration of DO is uniform throughout the water. He notes that this is usually achieved with diffused air systems but does not strictly apply for mechanical surface aerators. Hoyland[58] has recommended procedural modifications to account for DO variations in the water. He notes that the error will be relatively small if the variation in DO at any point in the tank, in comparison with the mean value of DO, is less than 10 percent of the DO deficit.

Standard Methods[2] notes that a single K_La value is reproducible within ± 15 percent of the mean for multiple aerators and ± 8 percent for a single aerator per basin. It is reported in Standard Methods[2] that if the DO concentration at all points is within 0.25 mg/ℓ of the average DO at time t, you may make one K_La determination. If not, then individual K_La values must be determined for each sample point. Non-parallel slopes indicate incomplete mixing, and the test results should be voided.

Smart,[5] in the Ontario Ministry of the Environment procedure for mechanical aerators, requires that the K_La values for each sample point shall not vary more than ± 10 percent from the average value. Greater variation shall indicate incomplete mixing and invalidate the test. Naimie et al.[16] report that the standard deviation of K_La data in their testing program was equal to about 7 percent of the mean K_La values obtained during bench, pilot, or full-scale aeration testing.

Boon[23] reports that the K_La variation should not be used as an indication of poor mixing. He states that the DO variation at each sampling point is a better indicator of poor mixing. He further states that the variation of K_La may be due to poor sampling procedure, inaccurate measurement of DO, changes in the "purity" of water, sulfite presence in the water, and/or non-uniform distribution of DO.

Shell[43] believes that uniform DO concentration throughout the basin is not a valid indicator of uniform or complete mixing. He states that since all aeration devices are point sources of oxygen transfer, an oxygen concentration gradient must exist across the aeration device and in the basin.

Section 8 on Geometry, Scale-Up, and Mixing presents discussion concerning the evaluation of mixing. This section notes that "DO gradients are intrinsic to the reaeration test and do not imply problems related to either mixing or mass transfer". It is further stated that "the rate of change in oxygen concentration with time (mg/ℓ hr) at various points within the test basin is the primary indicator of mixing conditions when compared to the mean value of all points". A coefficient of variation limitation is suggested in Section 8 as follows:

Test Conditions	Coefficient of Variation(%)
Factory	5
Field	10

The observation is made in Section 8 that satisfactory compliance with the limits will not constitute a guarantee of adequate mixing; however, it will define conditions of equal supply for DO throughout the basin.

Detergent Addition

As noted in the introduction to this section of the report, there are two primary reasons for consideration of an oxygen transfer test in clean water with detergent added. The first consideration is that of uncertainty due to variable water chemistry effects in field testing. It is suggested by Boon[59] that the addition of detergents overwhelms all the small effects caused by contaminants in the test water. He indicates that the total effect of the 5 mg/ℓ of detergent will swamp the effect of the fractional concentrations of other surface active agents that might be present in the water or the trace contaminant derived from an unclean aeration basin.

The second consideration is attempting to more closely simulate or predict the actual mixed liquor performance of the aeration system. Boon[59] has reported that the alpha values for fine bubble aeration systems (say 0.3

to 0.5) are significantly lower than surface air entrainment devices that have alpha values in the 0.85 to 1.20 range. While testing with detergent added does not yield the actual mixed liquor alpha for a given aeration device and set of test conditions, it does provide oxygen transfer performance results that may more closely predict actual operating performance.

Boon[60] has reported that testing in the United Kingdom is conducted in clean water and in clean water plus detergent. Approximately 80 percent of the testing is conducted under clean tap water conditions. He noted that detergent is added to tap water used for testing aerators for the reasons noted earlier. He also indicated that its use enables reproducible results to be obtained irrespective of the purity of the water; thus, tap water, river water, or final effluent may be used. Kayser[4] reporting on practices in West Germany and Austria indicated that clean water testing is commonly practiced. However, if the influence of detergents is desired, clean water with 5 mg/ℓ of anionic detergents is used.

In discussing the clean water plus detergent procedure utilized in the United Kingdom, Boon[60] states that household detergents are used to achieve an average concentration of anionic surfactant of 5 mg/ℓ. An initial concentration of about 7 mg/ℓ of anionic surfactant (expressed as Manoxol OT) is established after the addition of the cobalt solution and the sulfite deoxygenation step. The detergent is prepared as a concentrated solution in hot water and is uniformly dispersed into the test tank. The detergent concentration is measured in the test water at the beginning and end of the test. The goal is to achieve an average concentration of 5 mg/ℓ. For subsequent tests, cobalt is added each time, equivalent to 0.2 mg/ℓ of cobalt in the test water. Additional detergent is also added to achieve an initial detergent concentration of 7 mg/ℓ.

Ewing et al.[42] reported on testing with pure LAS. The results indicated that the concentration of LAS declined substantially (e.g., from 11 to 5 mg/ℓ) during each test and the results were quite varied, indicating poor reproducibility. The alpha values varied from 0.39 to 0.55 from the beginning to the end of the test. They stated that "this phenomenon, which dominated the tests using LAS, invalidates the analysis by the non-steady state method". They also observed that significant amounts of foam billowed about the test site. They further stated that "if such a test is to be meaningful, more work is required. Such work certainly seems justified because the use of the appropriate value of alpha is of great importance and constitutes one of the greatest areas of uncertainty and potential error in the present available predictive methods".

Gilbert[40] discussed the effect of surfactants on oxygen transfer rates and surface tension. Gilbert[40] cites several tests where alpha factors for "detergent-added" testing have varied with the type of aeration system. He notes that these results seem to support justification for use of a surface active agent in clean water tests.

However, Gilbert[40] states that "he sees no benefit in rating aerator performance with surface active agents present. The only accomplishment would be to introduce another variable to an already too-confused technical area". He cited the wide variation in types and concentrations of surface active agents in use. He also noted that the surfactant concentration decreases during a test run and the surface tension varies during a test run. Naimie et al.[16] stated that "the effects of detergent on the probe and Winkler K_La determinations for a variety of natural water systems would have to be quantified before they could support the inclusion of the addition of detergent to the test water in any proposed aeration testing standard".

Brenner[61] has stated that "if the addition of detergent will give us a handle on what might be expected in the actual field installation, we might be better off in the long run with standard tests that use detergent".

It appears that there are several valid reasons for conducting "added-detergent" testing despite the test uncertainties. Additional research and testing will hopefully clarify some of the uncertainties.

SULFITE OXIDATION

It has been suggested that the sulfite oxidation (or steady flow sulfite addition) method be discussed. Conway and Kumke[46] and Boon[27] have reported on the use of sulfite oxidation and have indicated that the transfer rates and efficiencies obtained are considerably higher (up to 40 percent) than those determined in clean water testing and are not related to the values obtained in mixed liquor. Boon[27] has noted that a steady flow sulfite addition method as reported by Schmit et al.[11] may be needed to evaluate oxygen transfer in a deep shaft system. Schmit et al.[11] suggested that the steady state flow method is applicable to other systems also and has several advantages over the unsteady state method.

RECOMMENDATIONS FOR STUDY

1. Additional investigation is needed to consider limiting geometry (e.g., minimum dimensions and maximum tank size).
2. Requirements regarding the required degree of mixing, if any, for valid oxygen transfer rate analysis should be evaluated. Subgroup B (Modelling and Data Interpretation) indicates that complete mixing is not needed, yet such a statement is cited as a requirement in some testing procedural descriptions.
3. Recommended procedures for air flow and power measurement should be refined. More information is needed regarding precision of measurements, best methods, type of calculation versus type of compressor, and brake versus line horsepower.
4. The area of water quality impacts requires considerable study. Work is needed to more clearly define which parameters have a significant impact on transfer rates and analytical measurements and in what concentrations. Existing information should be studied and additional experiments designed.

   Results of testing at variable TDS levels should be studied further to verify the type of testing limitation recommended.

   Cobalt effects should be restudied. Consideration of catalyst limitation and analytical interference need to be addressed.

   There should be an evaluation for which tests for surface tension should be used,and test conditions should be delineated.
5. The following questions should be addressed. What water quality adjustments can or should be permitted? Should pH limitations be established and test adjustments required? Can carbon be used to remove contaminants? What other measures should be considered?
6. Can drinking water standards (EPA and/or International) be used and modified to define "clean water" for testing?
7. Some additional development of quality control procedures for selection of sodium sulfite deoxygenation chemicals should be considered.

8. Experiences with varying early (up to 30 percent of C_{∞}^{*}) oxygen reaeration response data merit additional study to evaluate the cause and significance of the variabilities that have been reported.
9. Some additional refinements of pumped-sample procedures may merit study, e.g., pumpage rates, degassing, etc.
10. Oxygen transfer measurement. The Winkler DO procedure should be updated to reflect current Standard Methods committee findings and British experience. Topics to be addressed include cobalt interference, iodine vaporization, high TDS effects, "detergent-added" testing end-point clarity, and the meaning and significance of the "blank" procedure from the 1960 edition of Standard Methods.
    The DO probe procedure should be evaluated for potential interferences that have been reported, e.g., iron, manganese, dissolved gases. (Some re-evaluation is underway via the WPCF Standard Methods Subcommittee on Dissolved Oxygen). Should agitators be used for in-situ placement? The procedure for calibration and to ensure stability of readings could be more clearly described.
11. Additional testing and specially designed experiments using "detergent-added" procedures should be conducted to resolve uncertainties and more clearly describe the procedure. Consideration should be given to specifying a "standard" detergent mixture for addition to the test water.
12. Existing repetitive test data should be evaluated to further prescribe the acceptable precision for factory and field testing.
13. The usage and interpretation of K_La point variations and DO gradients during tests should be reviewed. How do they relate to mixing and/or test reliability?

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SECTION 6

EFFECTS OF ALPHA, BETA, AND THETA FACTORS AND SURFACTANTS ON SPECIFICATION, DESIGN, AND OPERATION OF AERATION SYSTEMS

INTRODUCTION

Many factors influence oxygen transfer mechanisms in wastewater treatment processes. Wastewater contaminants, temperature, dissolved oxygen (DO) concentration (driving force), type of aeration device, turbulence, and basin geometry all affect oxygen transfer rate. Since these factors make field application of an aeration device unique, it has become standard practice to specify aeration equipment at "standard conditions" and to develop additional techniques for adjusting rates at standard conditions to rates at field conditions.

Standard conditions in the United States are considered to be 20°C, 1 atm. barometric pressure, tap water, and zero DO concentration. In Europe, standard conditions are slightly different and 10°C is the standard temperature. Additionally, in the United Kingdom, a surfactant (commercial detergent) is used to change the properties of tap water to more closely approach the properties of wastewater and to mask the effects of trace contaminants in tap water.

Field oxygen transfer rates, OTR_f, are calculated from standardized oxygen transfer rates, SOTR, through the use of alpha, α; beta, β; and theta, θ factors. The factors are defined as follows:

$$K_La_{WW} = \alpha\ K_La_{TP} \tag{52}$$

$$C^*_{\infty WW} = \beta\ C^*_{\infty TP} \tag{53}$$

$$K_La_{20} = K_La_T\theta^{(20-T)} \tag{5}$$

where:

K_La = apparent volumetric mass transfer coefficient, t^{-1}
C^*_∞ = average DO saturation concentration attained at infinite time, mL^3
ww = subscript indicating wastewater
TP = subscript indicating tap water
T = subscript indicating a given temperature, T

OTR_f can be easily calculated from SOTR:

$$OTR_f = \left[\frac{\alpha(SOTR)\theta^{(T-20)}}{C^*_{\infty 20}}\right](\beta C^*_{\infty WW} - C_R) \tag{54}$$

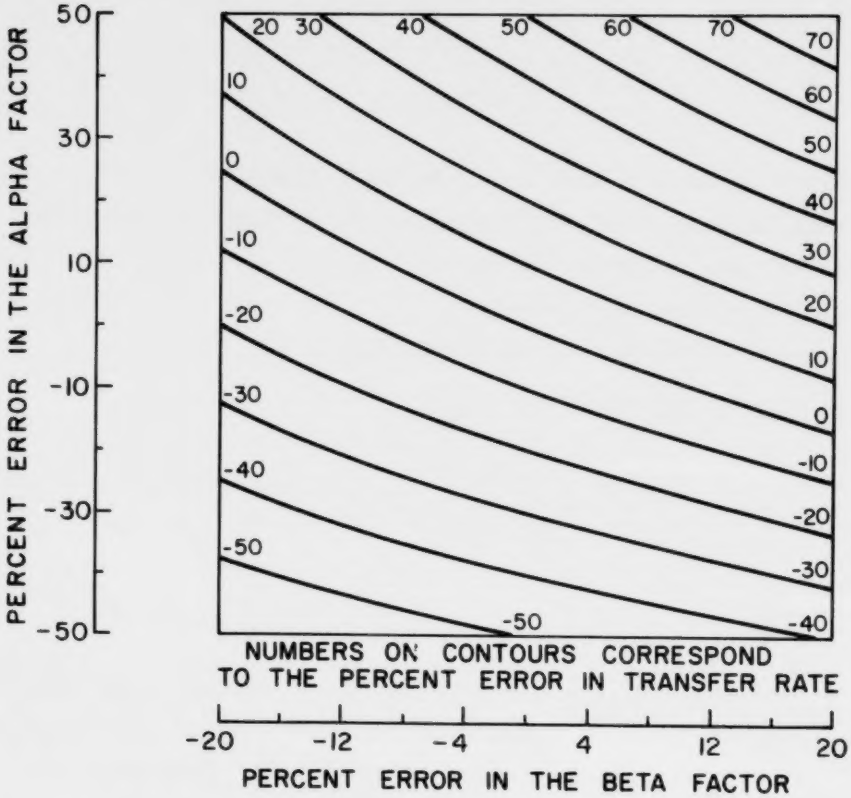
where:

C_R = desired DO concentration under normal operation, mL^3

Equation 54 differs slightly from Equation 48 in Section 4 in that the saturation temperature correction factor, τ, has been omitted for convenience to illustrate the influence of α, β, and θ on OTR_f. The importance of properly determining the alpha, beta, and theta factors cannot be overestimated. For example, the field transfer rate is only 52 percent of the standardized transfer rate when $C_R = 2$, $\alpha = 0.8$, $\beta = 0.9$, and T = 18° and assuming $\theta = 1.024$. Drastic over- or under-designed aeration systems can result if inaccurate correction factors are used. A profile of errors in field oxygen transfer rate for incorrect alpha and beta factors is shown in Figure 7.

It is extremely difficult to accurately determine alpha, beta, and theta parameters. It is not unusual for two individuals to measure very different factor values for a given wastewater. In addition, manufacturers and engineers have developed different methods for measurement, which result in differences in design and specification of aeration facilities.

The purpose of this section of the report, prepared by the Alpha, Beta, and Temperature Corrections Subgroup of the ASCE Subcommittee on Oxygen Transfer Standards, is to present the best available techniques for measuring and characterizing alpha, beta, and theta factors and the effect of



NUMBERS ON CONTOURS CORRESPOND TO THE PERCENT ERROR IN TRANSFER RATE

Figure 7. Error in field oxygen transfer rate as a function of errors in the measurement of the alpha and beta factors when alpha = 0.8 and beta = 0.9.

surfactants on aeration systems. The best available techniques have been selected by a consensus opinion of experts in the field of aeration -- consulting engineers, manufacturers, researchers, and academic professionals.

A review of the relevant background is presented in the initial portion of this section, followed by a review of important and recent findings by Subcommittee members and other researchers. The literature review and summary are to serve as partial justification for the Subgroup's conclusions.

ALPHA FACTOR

Several technical problems are associated with measuring the alpha factor as recently discussed by Gilbert.[1] The alpha factor varies with many process conditions, including wastewater quality, intensity of mixing or turbulence, suspended solids concentration, method of aeration, scale, and other factors. The effect of aeration methods is particularly important with respect to the alpha factor. It is not unusual to observe vastly different alpha factors using two different aeration methods for the same wastewater. It is worthwhile to document this claim from a historical perspective.

One of the first references to the dependence of the alpha factor upon aeration devices was made by Kessener and Ribbius.[2] They noted changes in oxygen transfer rate for two different methods of aeration using tap water and sterilized wastewater. They reported concentration versus time data, which can be used to calculate apparent mass transfer coefficients and alpha factors (Table 9).

It is obvious from the data presented in Table 9 that the alpha factor is quite different for the two aeration systems. Kessener and Ribbius[2] do not attempt to explain the reasons for the large difference in alpha factors, but indicate that such differences must be included in the design of aeration systems. It is also interesting to note that they proposed further research to determine if the influence of wastewater contaminants on oxygen transfer capacity should be included in aerator specifications.

The effect of aeration methods on alpha was demonstrated by Holroyd and Parker[3] using laboratory-scale devices. They used a mixture of tap water and several types of surfactants to show that diffused aeration was affected differently than mechanical surface aeration by water contaminants. They found that the alpha factor of a fine bubble diffuser (0.28-cm mean bubble diameter) could be as low as 0.5 in the presence of high surfactant concentrations (20 to 100 mg/ℓ). The same surfactant concentrations reduced the alpha factor of a 30-cm diameter disc surface aerator to only 0.8. Moreover, the different methods of aeration exhibited the greatest reductions in the alpha factor with different types of surfactants (i.e., cationic versus anionic).

Baars[4] has reported the effects of surfactants on fine bubble (approximetely 0.25-cm mean diameter) aeration. He found that commonly-used anionic and nonionic surfactants at 4 to 10 mg/ℓ concentration produced an alpha factor ranging from 0.9 to 0.4, respectively. The addition of anti-foaming agents reduced the alpha factor range from 0.8 to 0.35. Baars[4] also tested the Kessener brush aerator under similar conditions, finding that the alpha factor increased, ranging from 1.0 to approximately 2.0 for high surfactant concentrations. The addition of anti-foaming agents tended to reduce the

TABLE 9. APPARENT MASS TRANSFER COEFFICIENTS AND ALPHA FACTORS FOR THE DATA OF KESSENER AND RIBBIUS[2]

Method of Aeration	Liquid	K_La (min^{-1})	α
Kessener brush	Tap water	0.057	N/A
Kessener brush	Sterilized wastewater	0.047	0.82
Compressed air	Tap water	0.068	N/A
Compressed air	Sterilized wastewater	0.013	0.20

maximum alpha factors. Results similar to Baars[4] and Holroyd and Parker's[3] for fine bubble diffusers have been reported by a number of investigators, including Eckenfelder et al.,[5] Downing and Scragg,[6] Burgess and Wood,[7] O'Connor,[8] and Aiba and Toda,[9] as well as many others.

The results of Barnhart's[10] work (Figure 8), are particularly noteworthy because they illustrate the importance of bubble diameter. Barnhart[10] reports that the addition of surfactants reduces the bubble diameter until the critical micelle concentration is reached. Beyond the critical micelle concentration, very little reduction in bubble diameter occurs. Reduction in bubble diameter produces two distinct results: an increase in surface area per unit bubble volume and a decrease in terminal rise velocity. The decrease in terminal rise velocity results in longer bubble retention time, but reduces the surface renewal rate. The total of all mechanisms on alpha (reduction of film transfer coefficient, increase in surface area and retention time, reduction in surface renewal) has been estimated by Barnhart[10] for fine bubble diffusers. His estimates confirm the findings of field investigators such as Kessener and Ribbius,[2] who observed very low alpha factors. The oxygen transfer rate of fine bubble diffusers appears to be more reduced by surfactants than the transfer rate of other aeration methods since the bubble size cannot be further reduced by the surfactant.

The effects of surfactants on alpha have been investigated for various types of surface aerators. Downing et al.[11] investigated alpha factors for the Searle aerator (a modified brush-type aerator) and a Simplex Cone aerator (vertically rotating low speed surface aerator with draft tube).

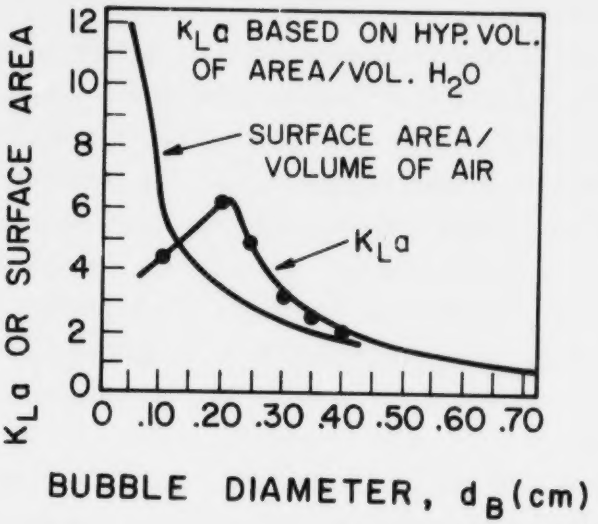


Figure 8. Effect of bubble size on mass transfer. This figure was taken from Barnhart.[10]

The alpha factor was approximately 2.0 for the Searle aerator in the presence of 10 mg/ℓ ABS. For the Simplex Cone aerator, they concluded that an increase in oxygen transfer rate of 10 to 15 percent could be expected with surfactant addition, which corresponds to an alpha factor of 1.1 to 1.15. They also report that anti-foaming agents reduced the alpha factor. Similar results have been reported by Eckenfelder and Ford[12] and von der Emde.[13]

The effects of surfactants on other types of aeration systems, such as static mixers and turbine aerators, have not been widely documented. Otoski et al.[14] have reported on the effects of surfactants on the alpha factor for static mixers. They found the alpha factor exceeded 1.0 at high mixing levels and decreased at low mixing levels. One manufacturer[15] has reported that the alpha factor for jets ranges from 0.9 to 1.2.

The mechanism of surfactant interference has been investigated by Mancy and Okun,[16] McKeown and Okun,[17] and Mancy and Barlage.[18] Mancy and Barlage[18] have shown that the effects of surfactants in aeration can be divided into two categories: the effect of the adsorbed surfactant film, which increases the resistance to transfer, and changes in hydrodynamic behavior of the air-liquid interface, which results from changes in surface tension produced by the surfactant. Included in this second category are changes in bubble dynamics and shape and reductions in surface renewal caused by the presence of the adsorbed surfactants.

Mancy and Barlage[18] used three experimental designs in their investigation: a 50-cm bubble column, a surface aerator, and a laminar jet orifice. With the laminar jet aerator, they were able to observe the effects of surfactants on the molecular diffusion coefficient independently of changes in hydrodynamic conditions. They demonstrated that hydrodynamic conditions, which are in large part created by the intensity of mixing, power input, and unique characteristics of each aeration device, will greatly affect oxygen transfer rate. Their results, which have been supported by Mueller[19] and others, explain why different types of aeration devices are affected differently by surfactants.

The work of Mancy and Barlage[18] also shows that the rate of surfactant adsorption (a function of the type of surfactant) to the gas-liquid interface will also affect oxygen transfer. Their results provide a partial theoretical basis for the observations of many other investigators. This phenomenon can be characterized by dynamic surface tension measurements. The commonly accepted du Nouy ring method for measuring surface tension indicates static surface tension and does not measure dynamic surface tension. Methods have been proposed to measure dynamic surface tension. Among these are the "ripple" method described by Mancy and Barlage[18] and various rate of bubble formation methods.

The alpha factor also changes substantially with wastewater characteristics. For example, Bass and Shell[20] report alpha factor fluctuations of 0.5 to 1.0 for various wastewaters and Eckenfelder[21] has reported the alpha factor for an industrial wastewater to vary between 0.3 and 0.8. The variance in alpha factor can largely be attributed to the changing characteristics of the raw wastewater with time of day or day of week. The results of an investigation by Katz[22] demonstrate this apparent time-varying of the alpha factor (Table 10); the data represent the results of a 3-mo comprehensive study of oxygen transfer rates. The K_La values were measured by off-gas analysis in a two-pass aeration tank approximately 15 ft deep by 45 ft wide by 370 ft long, equipped with fine bubble diffusers. It is not possible to calculate alpha factors from these data since the clean or tap water transfer rate is not known; however, a "transfer factor" has been calculated that

TABLE 10. VARIATION IN OXYGEN TRANSFER RATE AT THE JONES ISLAND TREATMENT PLANT*

Date	K_La [†] (days^{-1})	Transfer Factor [‡]
6/18/64	59.6	0.66
6/24/64	87.8	0.97
6/26/64	84.0	0.93
7/8/64	124.7	1.39
7/16/64	102.4	1.13
7/22/64	122.5	1.36
7/24/64	97.1	1.08
7/28/64	76.3	0.85
7/29/64	68.9	0.76
7/30/64	91.0	1.01
8/5/64	103.2	1.13
8/6/64	91.0	1.01
8/12/64	70.1	0.78
8/13/64	96.4	1.07
8/14/64	94.8	1.05
8/20/64	78.6	0.87
8/21/64	93.2	1.03
8/26/64	84.7	0.94
8/27/64	98.6	1.09
9/2/64	76.3	0.85

*After Katz.[22]

[†] Mean K_La = 90.1 days^{-1}; variance in K_La = 273 days^{-2}.

[‡] Transfer factor is the ratio of the observed transfer rate to the mean transfer rate.

represents the ratio of the daily measured transfer rate to the mean value of all measured rates. The transfer factor ranges from minimum of 0.66 to a maximum of 1.39. If the maximum observed transfer rate is approximately equal to the clean water transfer rate, then the range of observed alpha factors can be estimated as 0.47 to 1.0. The magnitude of this range is conclusive evidence for the need to characterize the variance of the alpha factor due to changing wastewater characteristics.

Kalinske[23] and Pfeffer et al.[24] report that the alpha factor also varies with the degree of treatment and with the location of sampling points in activated sludge aeration basins. Generally, the alpha factor is lowest for the influent wastewater and increases to a maximum for the effluent wastewater, although Marotte[25] has observed an opposite trend.

Suspended solids concentration has also been reported to affect alpha. Downing[26] experimented with a range of suspended solids concentrations from 0 to 3,000 mg/ℓ and found alpha decreased with increasing solids concentration. Holroyd and Parker[3] observed no change in alpha with additions of bentonite. It is not clear whether the solids themselves affect alpha or if the effect is produced by organics associated with the solids.

From the previous discussion, it can be concluded that:

1. The alpha factor is very strongly affected by the method of aeration, whether using bench-, pilot-, or full-scale equipment. It appears that different methods of aeration have different levels of turbulence and surface renewal, which produce a different response in the alpha factor in the presence of surfactants.

2. The time-varying nature of many municipal and industrial wastewaters causes large fluctuations in the alpha factor. Also, the alpha factor will not necessarily be the same for different locations within wastewater treatment plants. For municipal wastewaters and treatment systems, the alpha factor is usually lowest for the influent wastewater and highest for the effluent; however, this trend may not be true for industrial cases.

3. The literature contains many seemingly contradictory findings indicating that present knowledge is inadequate to explain and quantify the effects of process conditions on the alpha factor or that the effects on alpha are so variable that it is not possible to develop general guidelines. It is apparent that the effects of contaminants on the alpha factor must be evaluated on a case-by-case basis.

4. The scale of the equipment used to determine alpha can have profound effects on the results, as reported by Barnhart[27] and Otoski[28] among others. It has been reported by Matsch[29] that the effects of scale can be

partially eliminated if proper dynamic and geometric similarity are maintained, but this belief is not consensus of the Subgroup. Several investigators have advanced the opinion that alpha testing in laboratory or pilot-scale vessels should be performed at the same K_La as the proposed full-scale plant; however, for deep-tank aeration systems, an equivalent K_La in a small pilot- or bench-scale vessel can only be obtained at very different levels of turbulence and air flow rates. Utilizing the "equivalent K_La" approach could result in incorrect alpha measurement since it has been shown that the alpha factor is related to turbulence level.

5. The ability to measure alpha independently of scale is extremely desirable and should receive priority for development.

6. It must be emphasized that the alpha factor used for designing an aeration system will be a range of values and not a single number.

ALPHA FACTOR TESTING: AN ALTERNATE APPROACH

The previous discussion has shown that it is extremely difficult to determine meaningful alpha factors. An alternate approach has been suggested that should be considered. The British have developed a different set of conditions for specifying aeration equipment. They add 5 mg/ℓ of a synthetic anionic surfactant to test waters to simulate the contaminants in wastewater that affect oxygen transfer and to minimize the effects of trace contaminants in tap water which affect oxygen transfer. Using this test procedure, the British contend that more meaningful standard aeration rates are measured, which places less importance on proper alpha factor testing. This concept can be advanced by defining $\bar{\alpha}$ (alpha bar) for all types of aeration equipment.

This proposal has several advantages and disadvantages. The primary disadvantage is the length of time that would be required to develop a new standard in the United States based on a "detergent-added" approach. Undoubtedly, many years work would be required before all manufacturers could change testing procedures to accommodate surfactants. Additionally, more complex shop testing procedures place an additional burden upon manufacturers, especially small manufacturers. Nevertheless, developing such a standard could result in reduction of design error caused by improper alpha factor testing. This reduction could result because the magnitude of measured alpha factors would be much closer to unity, due to the inclusion of the effects of surface tension in the manufacturer's specifications. A new concept of defining the alpha factor could be used, based upon British practice, as follows:

$$\bar{\alpha} = K_La_{ww}/K_La_{TP+S} \quad (55)$$

where:

K_La_{ww} = mass transfer coefficient in wastewater
K_La_{TP+S} = mass transfer coefficient in tap water with a surfactant added

There are problems in defining a proposed standard for "alpha bar". Ideally, the quantity of surfactant used should reduce the tap water surface tension to less than 40 dynes/cm. However, the surface tension and surfactant concentration can change during aeration, which has been reported by Ewing et al.[30] among others. Surface tension measuring equipment is expensive and not easily transported. In addition, this approach does not specifically address the problem of alpha factor dependence upon turbulence and mixing intensity.

Many years of successful British practice represent a significant incentive to develop a "detergent-added" testing practice in the United States. "Detergent-added" testing procedures are also being evaluated in Germany and other European countries.

BETA FACTOR

The beta factor, β, has been defined as the ratio of the saturation DO concentration in wastewater to the saturation DO concentration in clean tap water:

$$\beta = C^*_{\infty ww}/C^*_{\infty TP} \quad (56)$$

An accurate value of saturation DO concentration is required to accurately estimate the oxygen transfer capability of an aeration device. Unfortunately, the saturation DO value is affected by a large number of variables and process conditions, including barometric pressure, temperature, suspended solids, dissolved organics, and dissolved solids. Many wastewaters contain sufficiently high dissolved solids concentrations to significantly reduce the saturation DO concentration.

The beta factor has been found to vary over a broad range, although variations are generally less than those reported for the alpha factor.

Eckenfelder et al.[5] have reported that the beta factor for domestic wastewater is generally about 0.95 and that it can vary over a much broader range for industrial wastewaters. For example, they measured the beta factor for pulp mill wastes using the Winkler test and found it varied from 0.77 to 0.97.

Significant technical problems exist in measuring beta factors. The most common wet chemical analysis for DO, the Winkler analysis (as specified by Standard Methods[31]), is subject to interferences that make the test ineffective for some types of wastewaters. Interferences have been reported by Kalinske[23] and Marotte[25] among others. Marotte[25] has found that the amount of manganous sulfate added to the sample for DO analysis may change the measured value of DO concentration. He has hypothesized that organic matter in some wastewaters may chelate metal ions, such as manganese or cobalt, thereby reducing their activity in solution and changing the measured DO.

It has been proposed that the DO probe be used to determine beta values. This alternative is attractive since the galvanic cell in a DO probe is isolated from the wastewater constituents that interfere with the Winkler test. Unfortunately, the DO probe cannot be used to measure beta factors since the probe responds to the activity of molecular oxygen and not concentration. This phenomenon has been discussed extensively by Carritt and Kanwisher,[32] Mancy and Westgarth,[33] and McKeown et al.[34]

An alternative method for measuring beta factors, which has been proposed by Bass and Shell[20] and several Subcommittee members, is to use an analytical correction factor based upon the total dissolved solids (TDS) concentration. With this technique, a wastewater must be measured for TDS before a beta value can be determined. Once the TDS concentration is known and corrections are made for barometric pressure and temperature, the beta factor can easily be calculated.

To determine the beta factor using the TDS concentration, it is necessary to refer to a table of saturation DO values. Using an abbreviated list of saturation DO concentrations (Table 11), it is possible to estimate the β factor. For example, if the TDS of a wastewater is measured as 10,000 mg/ℓ, the beta factor, at 25°C, can be calculated as the ratio of two saturation values:

$$\beta = 7.4/8.2 = 0.90 \quad C^{*}_{\infty(Cl\,=\,10{,}000)}/C^{*}_{\infty(Cl\,=\,0)} \tag{57}$$

Table 11. SATURATION DISSOLVED OXYGEN CONCENTRATIONS AT VARIOUS CHLORIDE LEVELS*

Wastewater Temperature (°C)	Chloride Concentration (mg/ℓ) 0	5,000	10,000	15,000
15	10.1	9.5	9.0	8.5
20	9.1	8.6	8.2	7.7
25	8.2	7.8	7.4	7.1
30	7.5	7.2	6.8	6.5

*From Standard Methods.[31]

Similar results can be obtained using a DO meter with salinity calibration capability. A number of popular DO meters have special calibration scales to compensate for salt concentration. Usually, the calibration scales are associated with the temperature correction potentiometer on the DO meter.

The need for temperature compensation arises from the dependence of a membrane's permeability on temperature. It can be readily observed that a change in membrane permeability also produces a change in cell current. Therefore, a manufacturer can design a DO analyzer that corrects for temperature as well as activity (indicated by salt concentration) using only one control. The mechanism of calibration can be explained from an analysis of electro-chemical theory. The steady state current of a galvanic cell oxygen analyzer can be computed as follows:

$$i = n_e \overline{F}_a (P_m/b) A \qquad (58)$$

where:

i = current (Amperes)

n_e = number of electrons transferred in cell reaction

$\overline{F}$ = Faraday = 9.649×10^4 (Coulombs/mole)

P_m = permeability coefficient (cm^2/sec), L^2t

b = membrane thickness (cm), L

a = area of electrode (cm^2), L^2

A = DO activity (g·moles/1000 cm^3)

The equation can be rewritten in terms of DO concentration:

$$i = n_e \overline{F}_a (P_m/b) rC \qquad (59)$$

where:

r = oxygen activity coefficient

C = DO concentration, m/L^3

In a dilute solution, the DO concentration is nearly equal to the DO activity and the oxygen activity coefficient has the value of unity. In concentrated salt solutions, the oxygen activity coefficient is greater than unity, indicating that the DO activity is greater than the DO concentration.

Several of the Subgroup members have indicated that beta factors other than unity have been measured using DO probes (without salinity corrections). The existence of this phenomenon has not been well documented and can only be explained by the presence of some contaminant in the test water that changes the saturation DO concentration but does not change the oxygen activity coefficient. This phenomenon, if it exists, is not known in the experience of the majority of the Subgroup members; however, if such a phenomenon occurs, it would be of extreme importance since considerable error in beta factor measurements could occur. Also this phenomenon could explain the low beta factors measured by Eckenfelder et al.[5] This subject should receive priority for further development.

THETA FACTOR

Temperature strongly affects aeration systems in a variety of ways. Perhaps the greatest effect is on the saturation DO concentration. This subject is well documented. The effects of saturation concentration are not included in the theta factor since they can be handled in the field transfer equations.

The theta factor has normally been used to relate mass transfer coefficients:

$$K_La_T = K_La_{20}\theta_G^{(T-20)} \qquad (60)$$

or:

$$K_La_T = K_La_0 + \theta_A \cdot (T-20) \qquad (61)$$

where:

K_La_T = apparent mass transfer coefficient at temperature = T, t^{-1}
K_La_{20} = apparent mass transfer coefficient at T = 20°C, t^{-1}
θ_G = geometric temperature correction coefficient
θ_A = arithmetic temperature correction coefficient
K_La_0 = intercept value for arithmetic correction model determined by regression of K_La_T versus T data

The geometric technique, Equation 60, is more commonly used. This technique of correcting for the effects of temperature on oxygen transfer is empirical and attempts to lump all possible factors, such as changes in viscosity, surface tension, diffusivity of oxygen, etc. This empirical approach has produced a great variety of correction factors. Some investigators report that the geometric model yields better correction; others report that an arithmetic model is preferred. A wide range of temperature correction factors is reported in the literature (Table 12).

The diversity of data in Table 12 points to the inadequacy of the simple temperature correction techniques of Equations 60 and 61. Undoubtedly, the range of thetas could be refined if a closer evaluation of the experimental conditions was made; however, a number of the investigations reported in Table 12 were made under very precise experimental conditions and very likely reflect a correct relation between K_La and temperature. The unavoidable conclusion is that presently-used temperature correction techniques are inadequate.

Alternate methods for correcting temperature effects have been proposed by Metzger[35] and Hunter.[36] Metzger[35] has shown that the effect of temperature is related to the value of K_La and has recommended correction factors as a function of K_La. This result is an implication of the temperature dependence of K_La upon turbulence as well as oxygen diffusivity. Hunter[36] has used a similar approach in relating the value of K_La to temporal mean velocity gradient:

$$v_G = \left(\frac{P/V}{\mu}\right)^{1/2} \tag{62}$$

where:

v_G = temporal mean velocity gradient, t^{-1}
P = power input, mL^2t^{-3}

TABLE 12. TEMPERATURE CORRECTION FACTORS

Temperature Correction Coefficient	Aeration System	Model Type*	Reference
1.047	Open channel	G	Streeter et al.[36]
1.024	Stirred tank	G	Elmore and West[37]
1.020	Stirred tank	G	Downing and Truesdale[38]
1.024	Stirred tank	G	Downing and Truesdale[38]
1.016	Stirred tank	G	Downing and Truesdale[38]
1.018	Channel	G	Streeter[39]
1.015	Channel	G	Truesdale and Van Dyke[40]
1.008	Channel	G	Truesdale and Van Dyke[40]
1.0192	Saran tubes and spargers	G	Bewtra et al.[41]
1.020	Diffused aerators	G	Barnhart[10]
1.02	---	G	Clark et al.[42]
1.024	---	G	Metcalf and Eddy[43]
1.028	Surface aerators	G	Eckenfelder[44]
1.02	Turbine and diffused aerators	G	Eckenfelder[44]
1.047	Surface aerators	G	Lakin and Salzman[45]
0.0284	---	A	Ward et al.[46]
0.0204	Stirred tank	A	Downing and Truesdale[38]
0.015	---	A	Truesdale and Van Dyke[40]

*G = geometric; A = arithmetic

V = volume, L^3

μ = absolute viscosity, $mL^{-1}t^{-1}$

This approach accounts for the effects of temperature on liquid viscosity and turbulence.

From a theoretical standpoint, the approach of either Metzger[35] or Hunter[36] is preferable; however, based upon present knowledge, it is not possible to include such a technique in a design standard. It has been shown that different aeration systems can have different characteristics in the presence of surfactants, and it is plausible that each type of aeration system has a different correction factor based upon temperature and turbulence. Therefore, more research and development is required before a temperature correction technique based upon turbulence can be used.

From the previous discussion, it can be concluded that no single temperature correction technique can be applied to all methods of aeration. Also, it is apparent that the effect of temperature on $K_L a$ results from changes in oxygen diffusivity in addition to other factors such as turbulence.

Substantial error can result from applying incorrect theta factors to a geometric correction technique (Figure 9). The deviation from unity increases rapidly as the range of temperature correction increases. It is obvious that the single most effective method for minimizing correction error is to avoid testing during extremes of water temperature.

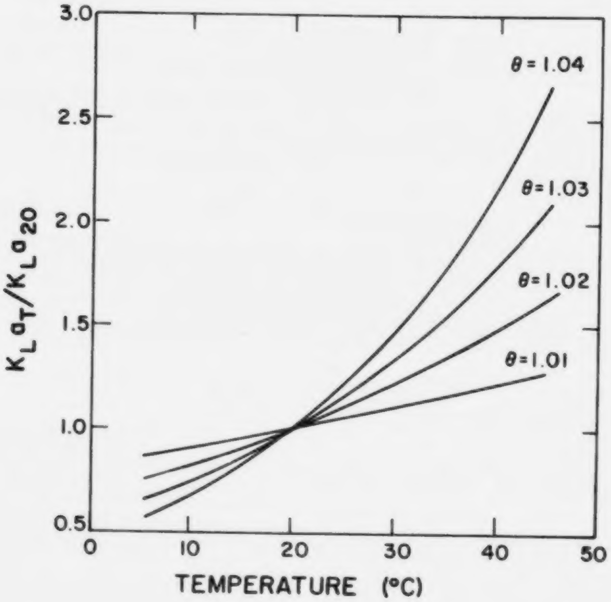


Figure 9. Effect of temperature on oxygen transfer rate.

APPARENT MASS TRANSFER COEFFICIENTS

Application of the experimental model to the analysis of unsteady state reaeration test data yields an apparent value of K_La, defined as K_La. In the case of surface aeration systems, the true and apparent values of K_La are equal. However, in subsurface gas injection systems, differences exist between the true and apparent values. Since α^* is defined by a ratio of true K_La values and α is defined similarly by a ratio of apparent K_La values, differences will also exist between values of α and α^*. The magnitude of these differences depends chiefly on the oxygen transfer efficiency of the subsurface gas injection system, with the greatest difference manifested at high efficiencies. For further discussion of this topic, the reader is referred to Section 4.

RESULTS AND CONCLUSIONS

From the previous discussion and literature review, it can be concluded that alpha, beta, and theta testing is at best an inexact science. There are many factors that are unknown or cannot be controlled in present test procedures. Consequently, the testing technique can greatly influence results. To reduce the discrepancies introduced by different techniques, an interim standard is proposed for determining alpha, beta, and theta factors. The proposed standard is based in part on the best available technology reported in the literature and in part on the scientific and engineering judgment of the Subgroup members. The Subgroup acknowledges that substantial updating of this proposed standard may be necessary and desirable before it achieves consensus status.

Alpha Factor

The alpha factor is influenced by a great number of process conditions, including surfactants, suspended solids, other wastewater characteristics, turbulence, geometry, scale, water temperature, and aeration method. The alpha factor ideally should represent the ratio of the performance of a given aeration system in wastewater to its performance in clean water. Therefore, it is desirable to eliminate the effects of geometry, scale, and turbulence. At present, it is not possible, or economically feasible, to specify a test procedure that will accomplish all objectives. The following alpha test procedure is proposed, therefore, based on the combined technical judgement of the Alpha, Beta, and Temperature Corrections Subgroup. It is recognized that the procedure is preliminary and subject to change.

1. The alpha factor is not constant and a series of measurements must be taken. Adequate aeration system design must consider the possible range of alpha factors likely to be encountered and an assessment of the risk associated with inadequate or excessive aeration capacity. Proper aeration system design cannot be made without knowledge of the range of alpha's to be encountered. It is recommended that a minimum of three tests be conducted.

2. Alpha testing must be performed using test devices similar to those being considered for actual design. This constraint is true at all scales of equipment. For mechanical aeration systems, the level of turbulence used in the test devices should be the same as the proposed design. A universal indicator of turbulence is not available, but several indicators have been suggested, such as Reynolds number, impellar tip speed, power input per unit volume, and power input per surface area. For diffused aeration systems, the test diffuser must produce bubbles that are the same diameter as those expected from the full-scale aeration device. Several tests should be made to determine the effect of turbulence or mixing intensity on the alpha factor.

3. The alpha factor can change with the degree of treatment. Ideally, the alpha factor should be determined using the actual fluids to be aerated. For example, in evaluating alpha for activated sludge plants, the mixed liquor should be used, including the suspended solids. Also for plug flow aeration systems, the alpha factor can change throughout the aeration tank. Proper design must account for this change. Conducting an alpha test using untreated influent is a poor second choice to using actual mixed liquor and often, but not always, results in lower alpha factors than are actually observed in full-scale operation.

4. The scale and geometry of test devices should be as close as possible to the actual design. It has been reported by one Subgroup member that the effects of scale can be modeled, but this opinion is not the consensus of the Subgroup.

The effect of scale on recently-developed devices such as static aerators and jet aerators, to the knowledge of the Subgroup, has not been investigated. Ideally, the alpha factor should be independent of the size and geometry of the device used for its determination.

5. Fresh wastewater samples should be used for alpha testing because sample characteristics can change very rapidly with time during storage.

6. Special considerations must be made with regard to depth of submergence in diffused air systems. In diffused aeration, three distinct phenomena occur: oxygen transfer during bubble formation, oxygen transfer from rising bubbles, and oxygen transfer at the surface. In full-scale systems, the first two mechanisms of transfer are significant and transfer at the surface is usually of small importance. With small-scale devices, the balance among the three methods can be very different, which can lead to serious errors in estimating alpha factors. For example, Schmit et al.[47] found that a bench-scale alpha factor of 1.0 was 33 percent higher than the alpha factor measured with full-scale equipment.

Several investigators, including Morgan and Bewtra,[48] Aiba and Toda,[9] Ippen and Carver,[49] and others, have demonstrated the effects of depth on oxygen transfer in diffused aeration systems. Their work should be consulted for further details.

7. Alpha testing can be performed for two purposes: process design or performance testing. During a performance test, many of the restrictions on alpha testing may be relaxed since only one value of alpha is needed at one point in time. Also, the endogenous phase of bacterial growth can be used for measuring alpha factors for performance testing. Endogenous-phase alpha factor testing can lead to erroneous aeration specifications if the resulting alpha factors are to be used for process design.

8. The likelihood of meaningful scale-up of small, lab-scale tests to full-scale systems is remote using current, state-of-the-art procedures. Full-scale testing should be performed whenever possible.

State-of-the-Art for Alpha Factor Determination

It is the consensus of the Subgroup that no method exists for measuring the alpha factor that is suitable as a standard procedure. However, it is possible to recommend standards of practice that will serve as a guide for alpha factor measurement. Methods for evaluating the alpha factor have been proposed by Barnhart,[27] Mueller,[19] Stukenberg et al.,[50] Bass and Shell,[20] and Gilbert;[1] the method proposed here draws heavily upon their work.

General Comments --

Alpha factor testing in small-scale vessels is at best only an educated guess to determine transfer conditions under process conditions. It has been stated previously by numerous investigators, most notably Kayser,[51] that alpha testing in small laboratory-scale vessels is unreliable and prone to inconsistencies and inaccuracies. Rigorous attention to detail and experimental technique can eliminate many of the inconsistencies, but even the best testing procedures are subject to error. Consequently, the alpha factors determined by the procedure recommended here and elsewhere are only approximate methods for obtaining process oxygen transfer rates.

General Conditions for Alpha Factor Testing --

To determine alpha factors for a wastewater to be aerated, one must first select the source of wastewater samples. For example, if the untreated wastewater is used, a lower alpha factor will generally be measured as compared to treated wastewater. Preferably, an alpha test should utilize the actual fluid to be aerated. For activated sludge systems, mixed liquor is the best choice for alpha factor testing.

The oxygen consumption of the sludge can be reduced to a constant rate by aerating the sludge until it is in the endogenous phase. In this manner, errors in measuring oxygen uptake rate can be minimized and an alpha factor for performance testing can be obtained. If it is desired to measure alpha factors for normal process operation, measurements in the endogenous phase should be avoided. Two alternatives are available: using settled mixed liquor, which will have a very low oxygen uptake rate, or using mixed liquor and attempting to accurately quantify the oxygen uptake rate. The reader is directed to Section 7 of this report on Oxygen Transfer Measurements in Respiring Systems where technique and errors associated with oxygen uptake are discussed. It is noted, however, that the presence of biological solids is thought to affect the alpha factor; therefore, the reader has to choose the method that he thinks will produce the least error. The use of untreated wastewater should be avoided, since erroneously low values of the alpha factor will probably result, although Marotte[25] has occasionally found the opposite to be true.

To properly measure alpha factors, it is imperative that alpha testing be performed with devices similar to those planned for the full-scale design. For example, fine bubble diffusers behave differently in the presence of surfactants than coarse bubble diffusers or mechanical aerators. To properly test for the alpha factor in diffused aeration systems, it is necessary to use a laboratory diffuser that produces bubbles the same diameter as the full-scale diffuser. This may be very difficult since the hydrostatic head at the diffuser will be different for the laboratory-scale device than for the full-scale device. Some investigators have recommended using the "equivalent K_La" approach for overcoming the problem, but this method is not recommended since different levels of turbulence are often required to achieve an "equivalent K_La".

Experimental Setup --

Bench-scale experimental setups for alpha factor testing are shown in Figures 10, 11, and 12 for turbine, diffused, and surface aeration, respectively. There are several essential features of each setup. The absorption vessel or reactor should be as large as possible to reduce the effects of scale. For field testing, it is often impractical to use reactors larger than 50 gal and, in many cases, even smaller reactors must be used. If cylindrical reactors are used, it is imperative that the vessels be baffled with four verticle baffles running from the reactor bottom to the surface. The baffles must extend from the wall into the reactor a distance of one-tenth of the diameter.

Methods for deaerating and measuring DO concentrations have been recommended by other Subgroups within the Oxygen Transfer Standards Subcommittee. Also, the recommended method for data analysis should be used in alpha factor determination. The pertinent other sections of this report should be consulted for standard procedures.

To perform alpha determinations, it is first necessary to determine the clean water performance of the aeration device. Clean water tests should be conducted using tap water, which is indicative of waters used for shop testing. Process waters that contain surfactants or waters that produce visible foaming during aeration will yield erroneous results. It is also

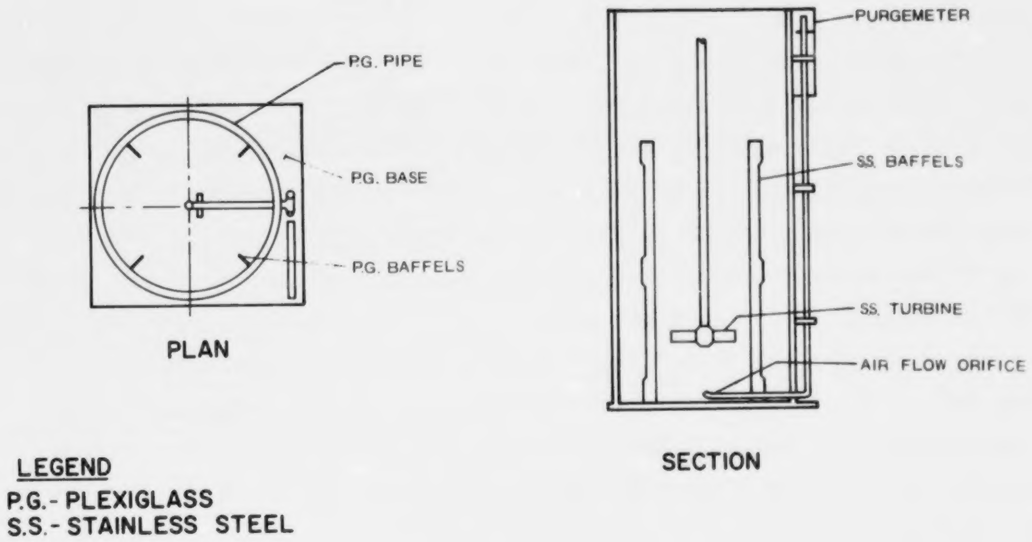

P.G. PIPE
P.G. BASE
P.G. BAFFELS
PLAN
PURGEMETER
S.S. BAFFELS
S.S. TURBINE
AIR FLOW ORIFICE
SECTION
LEGEND
P.G.- PLEXIGLASS
S.S.- STAINLESS STEEL

Figure 10. Diagram of bench-scale turbine aeration alpha test apparatus. This figure was taken from Stukenberg et al.[50]

imperative that the reactor and internals be cleaned prior to use to insure that all surfactants have been removed. Some investigators have found it extremely difficult to clean surfactant-contaminated equipment. The use of an absorbent, such as bentonite, will aid cleaning. If diffusers are used, two sets should be purchased, one for use with clean water and the other for process waters.

Turbulence Level --

The alpha factor has been shown to depend upon turbulence intensity. Unfortunately, it is not possible at present to precisely translate laboratory experimental results to full-scale applications; therefore, an attempt should be made to perform alpha testing at the same turbulence levels that are intended for the full-scale design. For example, Figures 13, 14, and 15 illustrate effects of power intensity on alpha factor measurements observed by Hwang[52] for turbine, diffused, and surface aeration, respectively. In performing alpha factor testing, it is necessary to ascertain the effects of

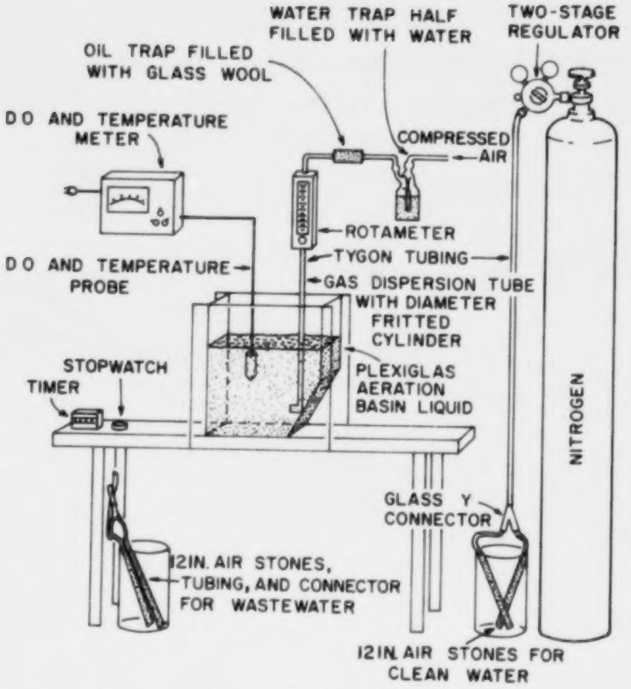

WATER TRAP HALF FILLED WITH WATER
TWO-STAGE REGULATOR
OIL TRAP FILLED WITH GLASS WOOL
D O AND TEMPERATURE METER
COMPRESSED AIR
ROTAMETER
TYGON TUBING
D O AND TEMPERATURE PROBE
GAS DISPERSION TUBE WITH DIAMETER FRITTED CYLINDER
STOPWATCH
TIMER
PLEXIGLAS AERATION BASIN LIQUID
NITROGEN
GLASS Y CONNECTOR
12IN. AIR STONES, TUBING, AND CONNECTOR FOR WASTEWATER
12IN. AIR STONES FOR CLEAN WATER

Figure 11. Diagram of bench-scale diffused aeration alpha test apparatus. This figure was taken from Bass and Shell.[20]

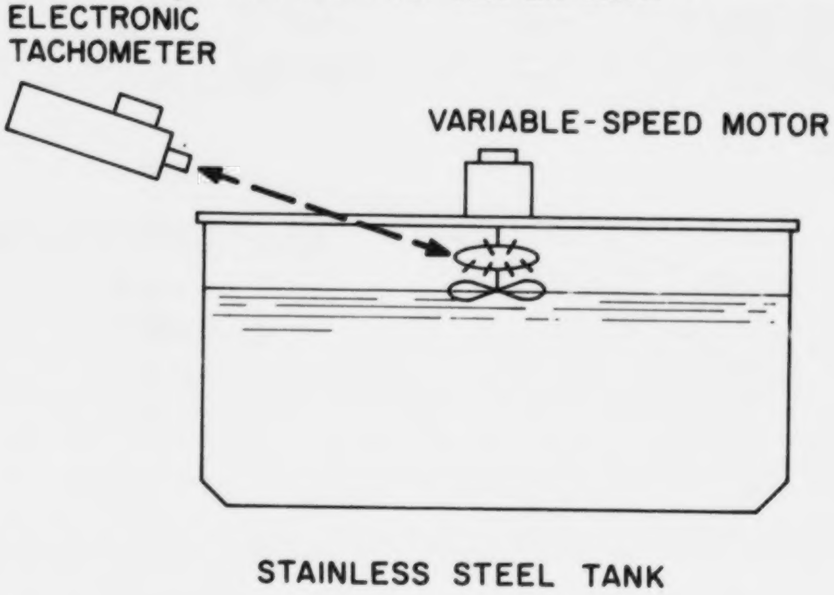

ELECTRONIC TACHOMETER
VARIABLE-SPEED MOTOR
STAINLESS STEEL TANK

Figure 12. Diagram of bench-scale surface aeration alpha test apparatus. This figure was taken from Bass and Shell.[20]

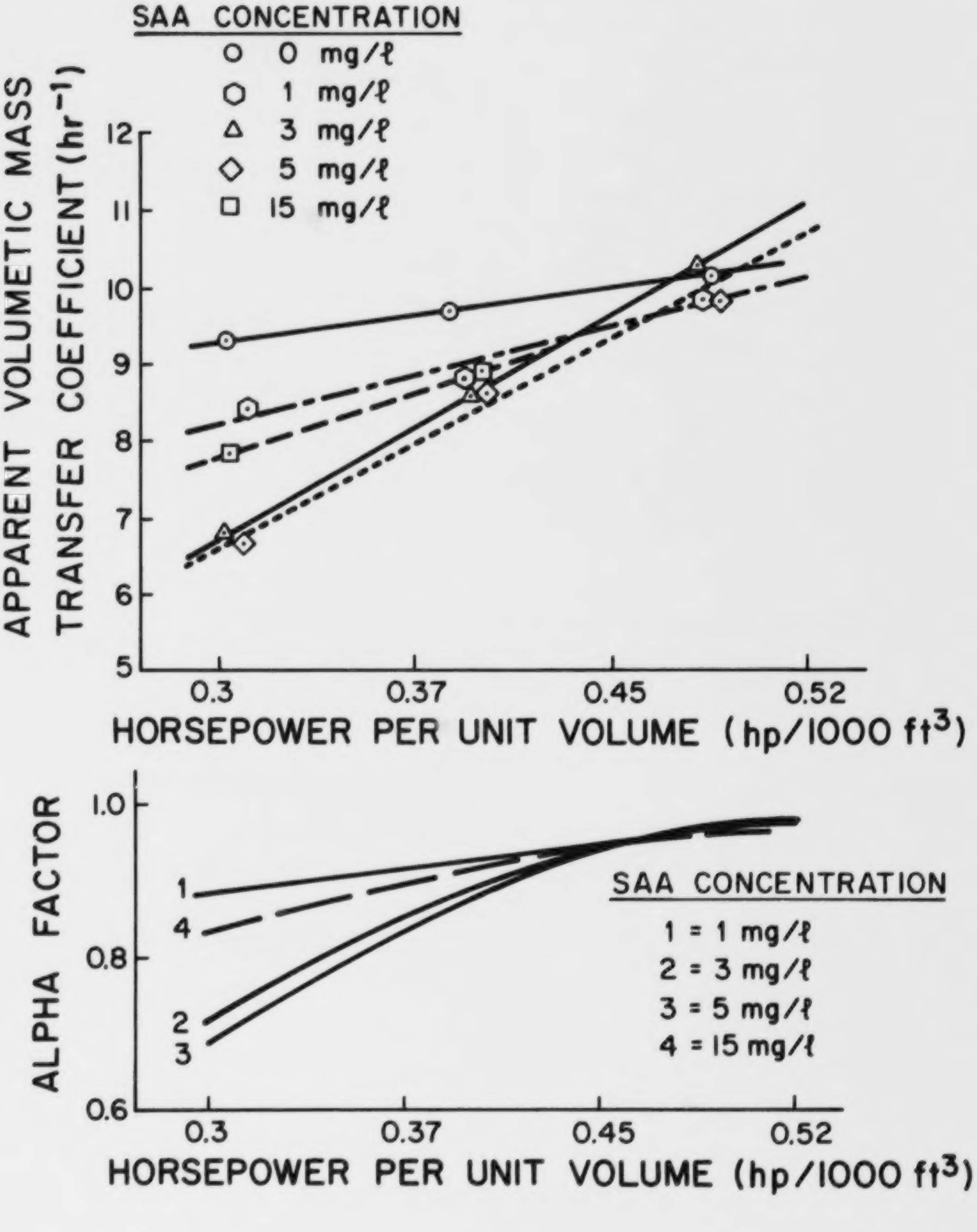


Figure 13. Gas transfer characteristics in a 50-gal vessel with turbine aeration in the presence of surfactants (dodecyl sodium sulfate).

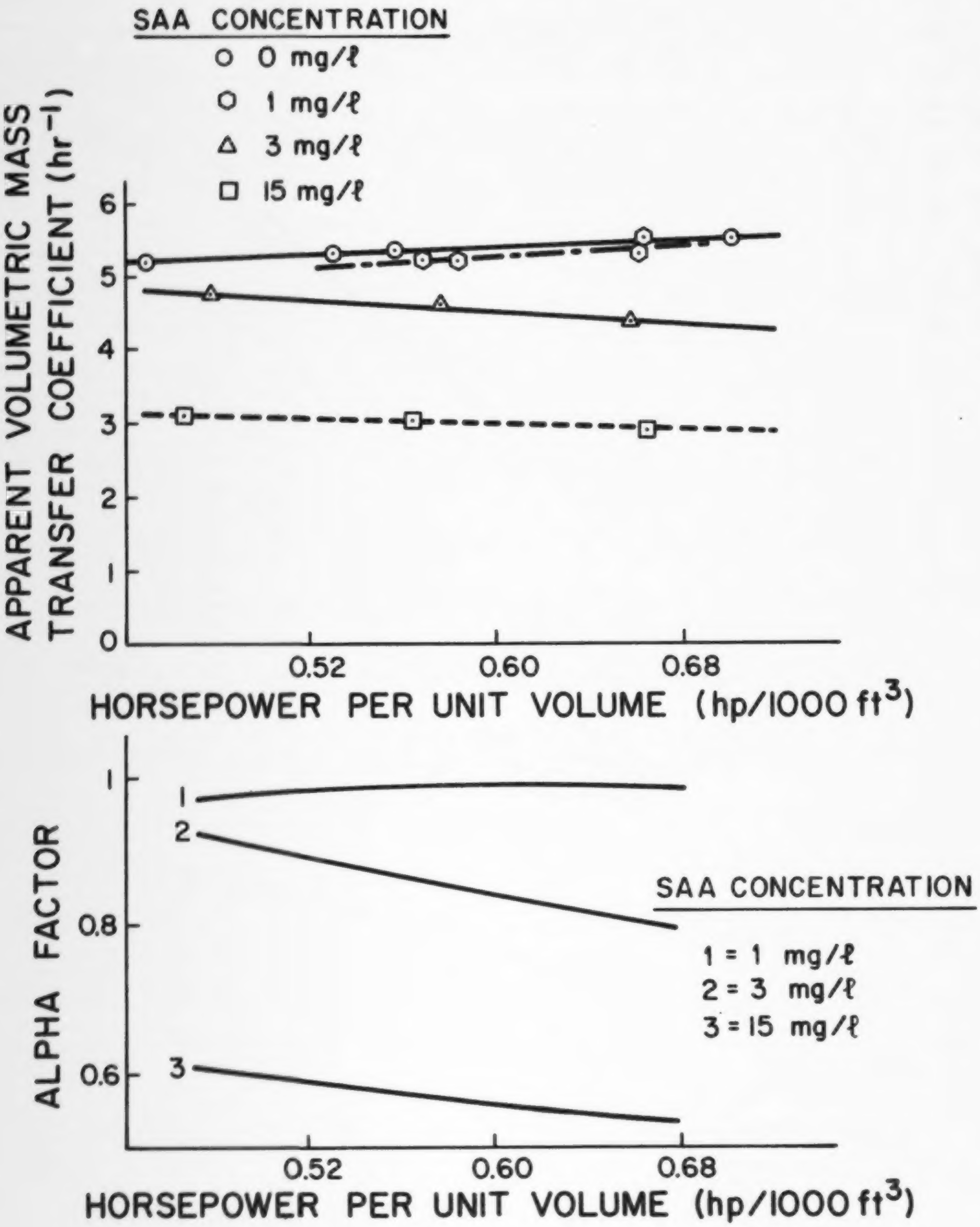


Figure 14. Gas transfer characteristics in a 50-gal vessel with diffused aeration in the presence of surfactants (dodecyl sodium sulfate).

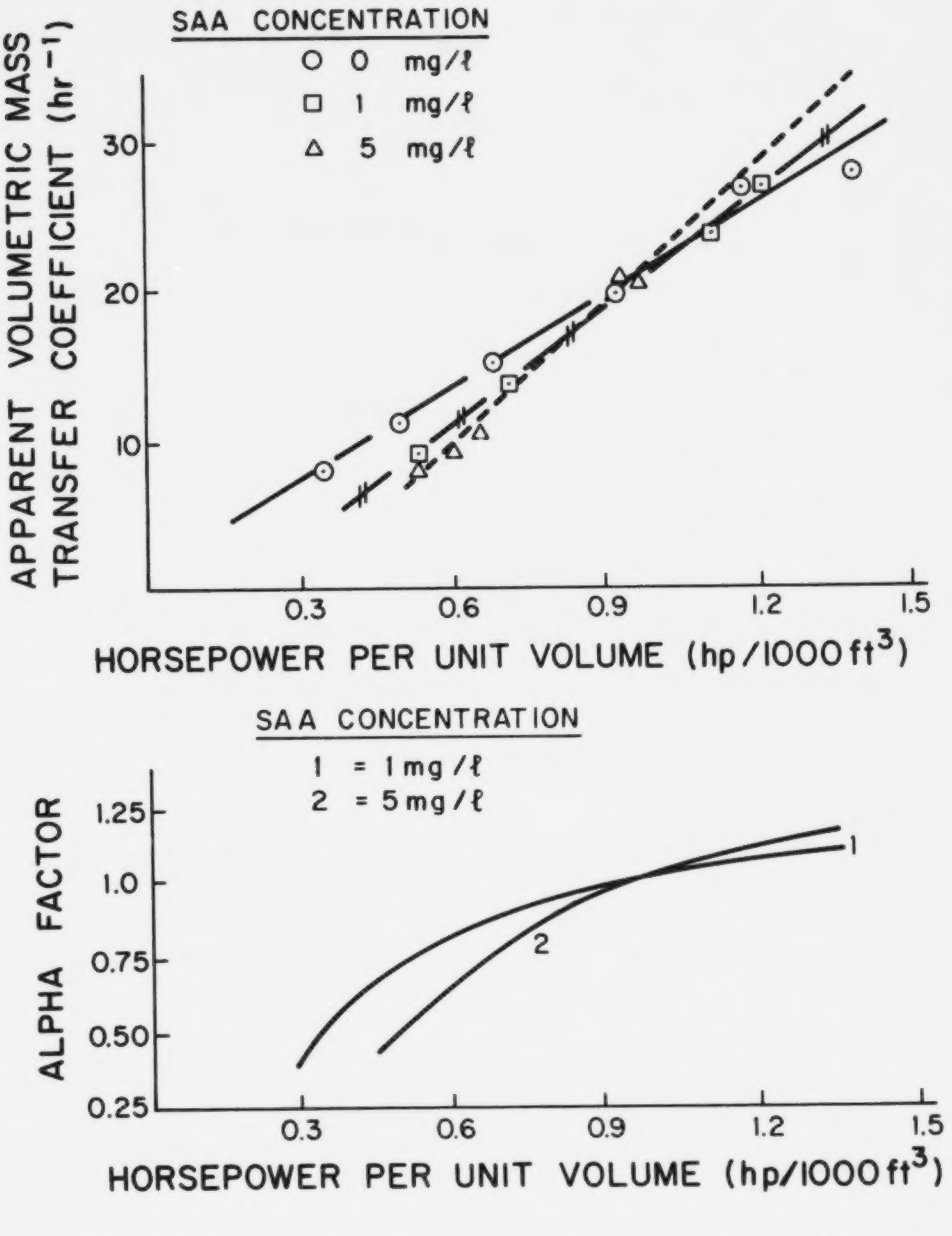


Figure 15. Gas transfer characteristics in a 50-gal vessel with surface aeration in the presence of surfactants (dodecyl sodium sulfate).

turbulence level or power input; therefore, several experiments (at least three) must be performed, each at a different turbulence level.

Measuring the power input level can be an extremely difficult and time-consuming job, especially if a variable-speed mechanical mixer is used. One must measure mixer rotational speed with a tacometer since a simple potentiometer setting is much too inaccurate for alpha testing. The power input to the mixer motor must also be measured. Minor changes in mixer impeller height can change the power the mixer is consuming and will lead to errors in alpha factor measurement if not considered. Additionally, for turbine aerators, the mixer power consumption will depend upon gas rate. Using single-speed mixer motors does not necessarily reduce errors since power consumption can still vary due to impeller placement and gas rate.

It is recommended that a mixer be used that is equipped with power input measuring devices. There are several such devices on the market costing \$500 to \$1000, which tends to make alpha testing very expensive. An alternate approach is to modify a variable-speed DC motor controller to indicate power. This can be achieved by adding a voltmeter in parallel with the motor and an ammeter in series with the motor. The exact arrangement will depend upon the type of DC motor used and will only be accurate in the upper ranges of the motor's power/speed range.

An additional problem in determining the alpha factor is its time-varying nature due to changes in the characteristics of the raw wastewater with time of day. It was shown in Table 10 that the alpha factor can change significantly over a period of time. To adequately characterize the alpha factor, it is necessary to conduct several experiments at different times. Preferably, at least three experiments should be performed using samples obtained at different times during the day.

Typical Values for the Alpha Factor --

A compilation of commonly-observed alpha factors for various types of wastewaters has been compiled by Barnhart[27] (Table 13). The alpha factors shown should only be regarded as observations and not guidelines for design.

Alpha factors have also been measured for several types of aeration devices (Table 14). Table 14 has been included in this section to inform the reader of previous work and not to provide guidelines for design or to

TABLE 13. ALPHA FACTORS OBSERVED BY BARNHART[27*†]

Wastewater Type	α
Municipal wastewater	0.8 - 0.95
Synthetic wastewater	0.8 - 0.85
Synthetic fiber	0.45 - 0.65
Apple processing wastes	0.8
Soap and detergent production	0.6 (raw); 0.85 (treated)
Oils and essence production	0.5 (raw); 0.9 (treated)
Paper (reworked)	0.65 - 0.9
Pulp and paper (Integrated mill)	0.7 - 0.8

[*] Alpha factors are reported for various types of devices at various conditions.

[†] The summary of alpha factors reported in this table is intended to illustrate the historical trends observed by previous investigators. The alpha factors reported here should not be used for design purposes, nor should they be used in lieu of testing.

serve as "standard" alpha factors.

Typical Procedures --

The following procedure serves as an example of the procedure recommended here.

Mechanical aeration --

1. Using manufactuere's data, determine the probable power level for the aeration system that is to be designed.

2. Using the unsteady state reaeration technique, determine K_La (or K_La^*) in tap water at power levels equal to 50 percent, 100 percent, and 150 percent of the probable power level calculated in Part 1. For turbine aerators, measure mixer speed, power level, and gas rate.

3. Using the liquid to be aerated in the full-scale design, determine K_La as in Part 2, using the same power levels. Impeller mixer submergence and speed should be controlled to obtain equivalent rotational speed and power input. For activated sludge mixed liquor testing, the oxygen uptake

TABLE 14. ALPHA FACTORS OBSERVED BY DIFFERENT INVESTIGATORS FOR DIFFERENT AERATION DEVICES*

Aeration Device	α	Comments	Reference
Fine bubble diffuser	0.4 to 0.6	5- to 10-ft tank depths; 10 to 30 scfm/1000 ft^3 (tap water with detergent)	Lister and Boon[53]
Brush	0.8	Calculated from their data (domestic wastewater)	Kessener and Ribbius[2]
Coarse bubble diffuser; sparger	0.7 to 0.8	10-ft tank depth; 80 to 190 scfm/1000 ft^3; 87,000-gal tank (tap water with detergent)	Gilbert[1]
Coarse bubble diffuser	0.65 to 0.75	22.5-ft tank depth; 25 to 92 scfm/1000 ft^3 (tap water with detergent)	Schmit et al.[47]
Static aerator	1.0 to 1.1	10-ft tank depth; 10 to 180 scfm/1000 ft^3; 87,000-gal tank (tap water with detergent)	Otoski[28] and Otoski et al.[14]
Surface aerators	0.6 to 1.2	Alpha factor tends to increase with increasing poser (tap water with detergent and small amounts of activated sludge)	Downing et al.[11]
Turbine aerators	0.6 to 1.2	Alpha factor tends to increase with increasing power; 25-, 50-, and 190-gal tanks (tap water with detergent)	Hwang[52]

*The summary of alpha factors reported in this table is intended to illustrate the historical trends observed by previous investigators. The alpha factors reported here should not be used for design purposes, not should they be used in lieu of testing.

rate stabilizes at a constant value (endogenous phase). It should be noted that alpha factors measured during the endogenous phase may be different from those measured during the growth phase.

4. For best approximation of the range of alpha factors, several series (at least three) of tests should be performed at different times. Also, alpha testing should be performed with samples from various points in plug flow aeration tanks. Alpha factors measured on respiring samples in the growth phase are subject to errors in measurement of oxygen uptake. The engineer must choose between using mixed liquor or settled mixed liquor and the errors associated with each procedure.

Diffused aeration --

1. Using manufacturer's data, select a diffuser for alpha testing that produces bubbles the same diameter as the intended full-scale diffuser. Also, determine the probable power level as previously.

2. Determine K_La in clean water as before, using power levels of 50 percent, 100 percent, and 150 percent of the probable power level.

3. As previously.

4. As previously.

Additional Procedures for Alpha Factor Determination

Additional procedures used for alpha factor determination are listed in Appendix C. These procedures were included as additional guides to individuals unfamiliar with alpha factor testing. They were selected because they represent state-of-the-art approaches to alpha testing; however, they are not recommended as proposed consensus methods. The procedures should be used as a "first draft" of an alpha testing procedure to be modified for each individual use.

State of the Art for Beta Factor Determination

The beta factor can be measured using the Winkler test method if it can be demonstrated that no interferences exist. In the event that chemical interferences exist, the beta factor should be calculated from a TDS measurement. Since the beta factor can vary with wastewater quality, a series of tests must be performed to obtain a range of beta factors. This range must be included in an overall system design and risk assessment, as indicated for the alpha factor.

State of the Art for Theta Factor Determination

No consensus exists for a temperature correction factor. The results of a review of the literature indicate that geometric temperature correction factors can range from 1.008 to 1.047 and that some aeration systems have mass transfer coefficients that are linearly related to temperature (as opposed to the geometric relation). Furthermore, it has been shown that the temperature correction factor is dependent upon turbulence.

It is recommended that a theta factor of 1.024 be used unless it is known that a different geometric theta factor is more suitable. Consultants and manufacturers who use theta factors other than 1.024 should be prepared to support their position with substantive data. It is also recommended that temperature corrections greater than 10°C be avoided, although it is recognized that sometimes this may be impossible. The error that can occur if incorrect theta factors are used and how the error is compounded if temperature corrections greater than 10°C are made were previously illustrated (Figure 9). For example, by using a theta factor of 1.032 instead of 1.024, the oxygen transfer rate will be overestimated by 12.5 percent.

FUTURE EMPHASIS AND RESEARCH NEEDS

Many uncertainties surround the selection of alpha, beta, and theta factors. This review has pointed out many of those uncertainties and should be used to define research needs. Two very high priorities are the needs for better models to explain the effects of turbulence on both the alpha and theta factors. Also, a fundamental analysis of the effects of scale is needed.

It is hoped that manufacturers will assume a position of leadership in the establishment of alpha bar factors ($\bar{\alpha}$) by running shop tests with detergent-spiked tap water. A better understanding will undoubtedly result if such information is developed and published.

Specific research needs have been identified that should be addressed:

1. Bench-scale alpha testing equipment should be developed that can be scaled to accurately predict the alpha factor for full-scale equipment.

2. A comprehensive evaluation of the trace contaminants in tap water for various locations in the United States and elsewhere should be undertaken. It is necessary to determine the magnitude of the effects of these contaminants on clean water oxygen transfer.

3. Portable analytical equipment for measuring such parameters as dynamic surface tension, bubble size, and mixer horsepower should be developed. The successful development and use of such equipment will reduce the variability of alpha testing.

4. Detergent testing should be performed to determine its suitability as a standard procedure in the United States.

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SECTION 7

OXYGEN TRANSFER MEASUREMENTS IN RESPIRING SYSTEMS

OBJECTIVES

Adequate test procedures must be available to permit the investigator to assess aeration equipment performance in respiring biological systems. Several test methods have been employed in the field to determine oxygen transfer. The twofold objectives of this section are: (1) to present a state-of-the-art review of the most commonly-used methods for determining the rate of oxygen transferred in respiring biological systems and (2) to discuss the limitations of each method.

BACKGROUND

Virtually all of the methods discussed herein have been tested in either pilot- or full-scale respiring systems. The methods span a multitude of biological treatment approaches, e.g., from high-rate activated sludge to aerated stabilization basins. In general, the methods can be categorized according to the rate of change of dissolved oxygen (DO) in a given reactor (or segment of reactor). Systems in which the rate of DO change is zero at any given point are referred to as steady state systems; the others are classified as unsteady state systems. In some cases, influent wastewater may be diverted from a reactor being tested. These are referred to as batch tests. The term "continuous test" is used for those cases where the influent wastewater flow is not diverted.

Three respiring system test methods do not require a direct measure of the oxygen uptake rate. These have been broadly categorized as the mass balance method, the off-gas method, and the tracer method. The mass balance method requires data on the net change in oxidation level between all entering and exiting liquid flows. The off-gas method is simply a mass balance on oxygen that includes both the liquid and gas streams. The tracer method indirectly measures the rate of oxygen transfer by determining the rate of transfer of a radioactive tracer.

The most commonly-used methods do involve the direct measurement of the oxygen uptake rate, R, of a respiring biological system. Two of these methods are carried out with little or no variation in DO in either batch or continuous flow systems; these are referred to as "Steady State Batch Tests" and "Steady State Continuous Tests," respectively. In the remaining two tests, the DO level in the reactor is adjusted at the beginning of the test to be either greater than or less than the steady state DO. These tests are referred to as "Unsteady State Batch Tests" if the influent wastewater flow is discontinued for the test and "Unsteady State Continuous Tests" if the influent wastewater flow is continued during testing.

The relationship between the steady state and unsteady state tests (either batch or continuous) may be readily seen from a hypothetical example (Figure 16). In Figure 16, the concentration of oxygen at one point in a reactor (designated as $\hat{C}$) is shown to decrease from $\hat{C}_{R1}$ to $\hat{C}_{min}$ after the aeration equipment is turned down and then is shown to increase from $\hat{C}_{min}$ through $\hat{C}_o$ to $\hat{C}_{R2}$ after the aerators are turned back up ($\hat{C}_{R1}$ may or may not be equal to $\hat{C}_{R2}$). The concentration $\hat{C}_o$ simply designates the DO concentration corresponding to time t_o, the time at which the investigator decides to initiate the full spectrum of data analyses. The DO concentration obviously increases whenever the supply of oxygen exceeds the rate of biological consumption, remains constant when the two rates are equal (in this case, at $\hat{C}_{R1}$ or $\hat{C}_{R2}$), and decreases when the consumption rate exceeds the supply rate. In clean water testing, sodium sulfite is used to reduce the DO level. In clean water, however, the rate of oxygen consumption is zero after time t_o, with the test proceeding to equilibrium at the effective system saturation concentration, C^*_∞. In a respiring system, the steady state concentration of oxygen, $\hat{C}_{R2}$, is reached at time t_o plus t_R. Note that the effective saturation concentration of oxygen that would result in the mixed liquor for a zero respiration rate is given in Figure 16 as $C^*_{f\infty}$.

THEORETICAL DEVELOPMENT

In order to both properly analyze the data generated from many of the test methods and understand those assumptions that are required for ease of

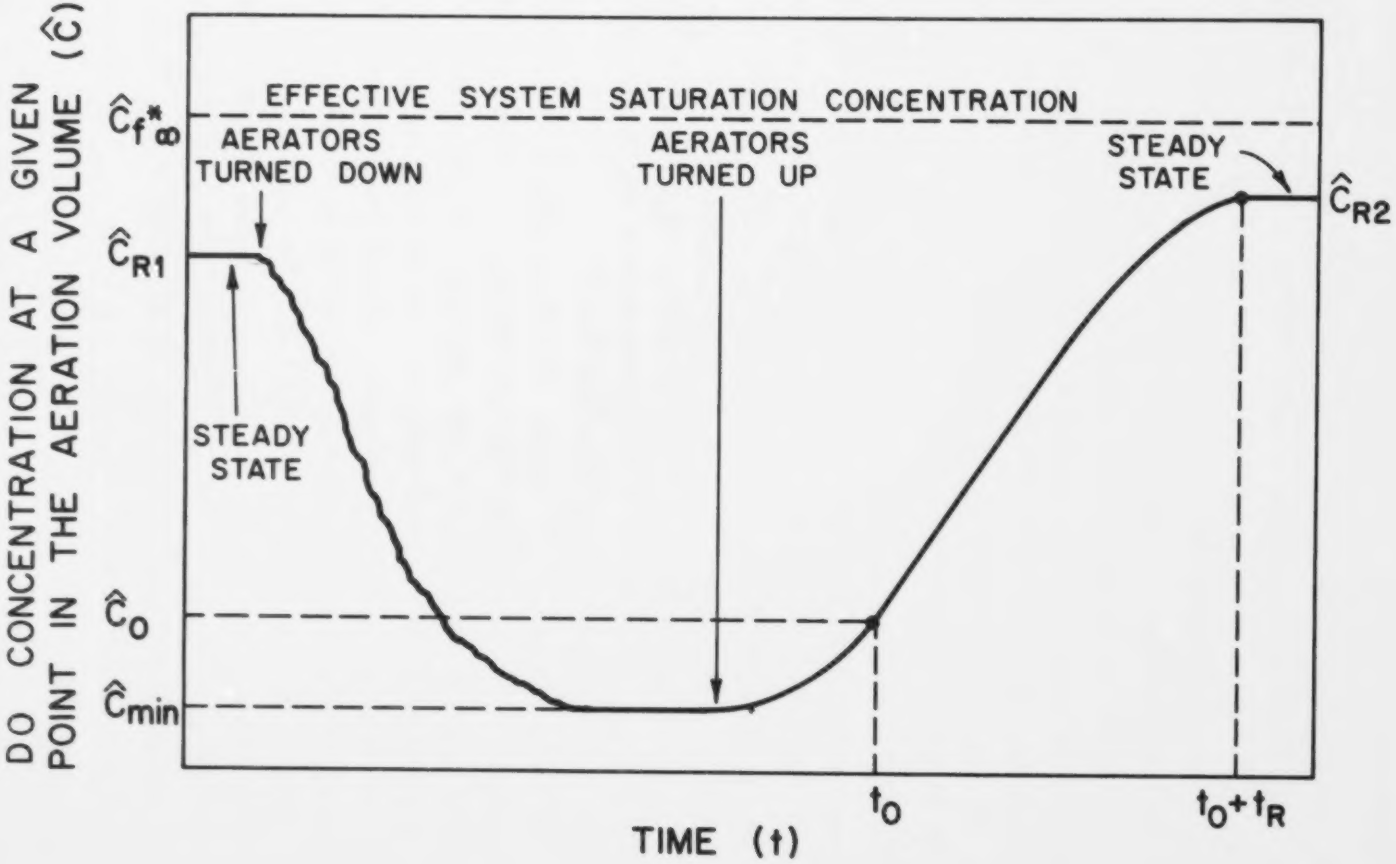

Figure 16. DO versus time for a respiring system with varying aeration conditions.

data handling, material balances are developed for continuous flow and batch reactors. General schematics for both continuous flow and batch systems are presented in Figure 17 along with definitions of the selected symbols. The remaining symbols are defined in the Symbols and Nomenclature list for the entire report. As can be seen from the figure, the term "batch" refers to the liquid phase only. Batch analysis allows for recycle of sludge solids but requires that there be no net liquid flow.

Many simplifying assumptions are required to develop practical equations that may be used to analyze the data collected in aeration testing. As a result, this section is purposely abbreviated to relate the general sense of the major assumptions without the more theoretical arguments. The first simplification is at the reaction level. Reactions rates are presented as arbitrary functions for three reactions: aerobic growth of heterotrophs, death and endogenous respiration, and nitrification (to nitrate nitrogen only with the impact of nitrite nitrogen ignored). Thus, $r_1(S,X)$ is the rate of carbonaceous substrate utilization in the growth reaction, $r_2(X)$ is the rate of organism death in the endogeneous reaction, and $r_3(N,X)$ is the rate of ammonia nitrogen oxidation in the nitrification reaction. The overall rates of oxygen consumption, R; substrate utilization, R_S; organism growth, R_b; and ammonia nitrogen utilization, R_N, are given by:

$$(-R) = -y_1 r_1(S,X) - y_2 r_2(X) - y_3 r_3(N,X) \qquad (63)$$

$$(-R_S) = -r_1(S,X) \qquad (64)$$

$$R_b = +y_{b1} r_1(S,X) - y_{b2} r_2(X) + y_{b3} r_3(N,X) \qquad (65)$$

$$(-R_N) = \pm\, y_{N1} r_1(S,X) + y_{N2} r_2(X) - y_{N3} r_3(N,X) \qquad (66)$$

where:

r_1, r_2, and r_3 are positive functions with:

$$r_1(S,X) = r_1(X) \quad \text{for} \quad S \geq S_{max}$$
$$r_3(N,X) = r_3(X) \quad \text{for} \quad N \geq N_{max}$$

S_{max} and N_{max} are the concentrations of carbonaceous substrate and

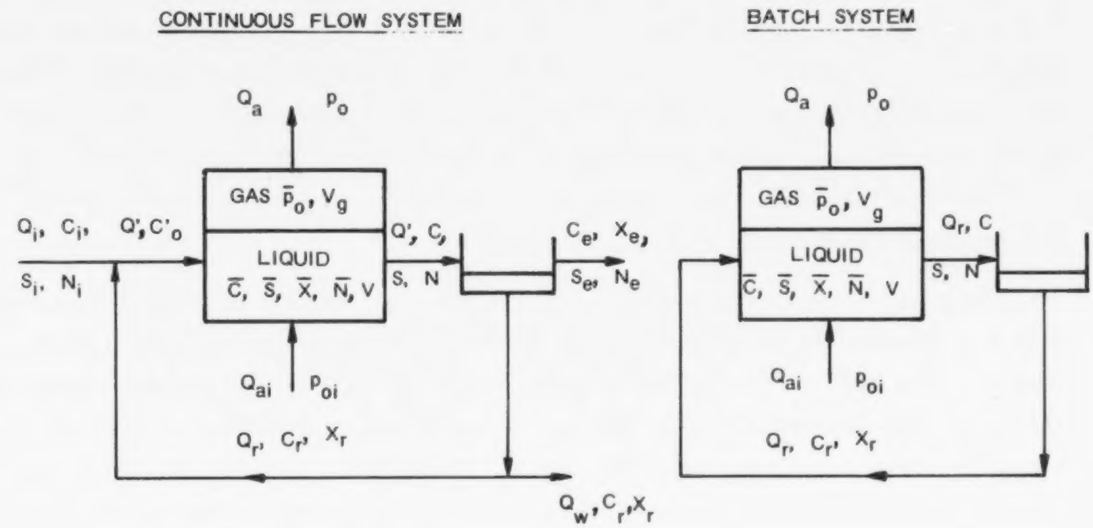
CONTINUOUS FLOW SYSTEM
BATCH SYSTEM
Q_a
p_o
GAS $\bar{p}_o$, V_g
LIQUID
$\bar{C}$, $\bar{S}$, $\bar{X}$, $\bar{N}$, V
Q_i, C_i, Q', C'_o
S_i, N_i
Q', C,
S, N
C_e, X_e,
S_e, N_e
Q_{ai}
p_{oi}
Q_r, C_r, X_r
Q_w, C_r, X_r
Q_a
p_o
GAS $\bar{p}_o$, V_g
LIQUID
$\bar{C}$, $\bar{S}$, $\bar{X}$, $\bar{N}$, V
Q_r, C
S, N
Q_{ai}
p_{oi}
Q_r, C_r, X_r

Figure 17. General schematics and nomenclature for continuous flow and batch respiring systems.

SYMBOLS

- C, S, X, and N represent concentrations in the liquid phase of oxygen, substrate, biological organisms, and ammonia nitrogen, respectively.
- C_R will be used to designate the steady state concentration of oxygen at a biological uptake rate of R.
- Q and Q_a represent flow rates for liquid streams and gas streams, respectively. Q_w represents the flow rate for waste activated sludge.
- p_o and p_{oi} represent the partial pressures of oxygen in the gas phase in the reactor and in the inlet, respectively.
- V and V_g represent the reactor volumes of the liquid and gas phases, respectively.
- The subscripts i, o, r, and e in the liquid phase are used to designate the influent wastewater, the combined streams entering the reactor, the recycle sludge flow, and the secondary clarifier effluent, respectively. No subscripts are used for either reactor concentrations or reactor effluent concentrations. A bar (e.g., $\bar{C}$) is used to represent spatially averaged concentrations of all reactor concentrations. Note finally that the symbol Q' is used to designate the liquid flow entering and leaving the continuous flow reactor (instead of Q_o). Q_o has been defined otherwise in a previous section.

nitrogen substrate, rexpectively, that define non-substrate limiting conditions.

The y's represent stoichiometric coefficients (always positive) that relate the relative mass of each component's utilization in each reaction. For example, y_1, y_2, and y_3 represent the mass of oxygen utilized per unit mass of substrate utilized, per unit mass of organisms decayed, and per unit mass of ammonia nitrogen utilized in the growth, endogenous, and nitrification reactions, respectively. Furthermore, the $\pm y_{N1}$ acknowledges that, in some instances, a net quantity of ammonia nitrogen may be produced from the growth equation due to organic nitrogen (therefore, the plus sign) or that a net quantity may be incorporated into a cell mass (therefore, the minus sign).

In this reaction scheme, the rate terms are constant whenever X is constant and either S and N are constant or above their respective non-substrate limiting concentrations.

The general mass balance on oxygen for the liquid phase is given in Equation 67 for a continuous flow reactor and in Equation 68 for a batch reactor with C at t = 0 equal to C_o for both equations:

$$V\left(\frac{d\bar{C}}{dt}\right) = Q'(C'_o - C) - VR + VK_La_f(C^*_{\infty f} - C) \qquad (67)$$

$$V\left(\frac{d\bar{C}}{dt}\right) = Q_r(C_r - C) - VR + VK_La_f(C^*_{\infty f} - C) \qquad (68)$$

For completely mixed reactors, $\bar{C}$ is equal to C.

The equations used to analyze results from field tests for steady state and unsteady state conditions result directly from Equations 67 and 68. The assumptions required to develop these equations are described in Tables 15 and 16 for both batch and continuous tests. Many of the assumptions, especially for the continuous flow systems, may not be valid. The validity of the assumptions is discussed in the subsections dealing directly with the test procedures.

Steady State Continuous Test

$$0 = Q'(C'_o - C_R) - VR + VK_La_f(C^*_{\infty f} - C_R) \qquad (69)$$

TABLE 15. ASSUMPTIONS NECESSARY TO DEVELOP EQUATIONS FOR STEADY AND UNSTEADY STATE BATCH TESTS

Assumptions	Steady State Test Condition	Unsteady State Test Condtiion
(1) Aeration volume DO, C_R, is constant	Steady state conditions have been achieved and maintained.	--
(2) Recycle sludge flow, Q_r is constant or zero	Recycle flow rate maintained constant or discontinued .	Recycle flow rate maintained constant or discontinued.
(3) Recycle DO, C_r is constant	Steady operation of recycle system if in use during the test period (e.g., sludge blanket level constant).	Steady operation of recycle system if in use during the test period (e.g., sludge blanket level constant).
(4) Aeration volume oxygen uptake rate, R, is constant	Aeration volume biological solids, X, and recycle sludge flow, Q_r, remain constant; carbonaceous, S, and nitrogenous, N, substrates are near zero during the test (if nitrification occurs in the test system).	Aeration volume biological solids, X, and recycle sludge flow, Q_r, remain constant; carbonaceous, S, and nitrogenous, N, substrates are near zero during the test (if nitirification occurs in the test system).
(5) Effective oxygen transfer rate, K_La_f, is constant	Carbonaceous substrate, S, is near zero during the test; alpha, α, value remains constant during the test period.	Carbonaceous substrate, S, is near zero during the test; alpha, α, value remains constant during the test period.

TABLE 16. ASSUMPTIONS NECESSARY TO DEVELOP EQUATIONS FOR STEADY AND UNSTEADY CONTINUOUS TESTS

Assumptions	Steady State Test Condition	Unsteady State Test Condition
(1) Aeration volume DO, C_R, is constant	Time of test short.	--
(2) Reactor influent flow, Q', is constant	Time of test short; variation in influent wastewater flow, Q_i, is negligible during test period; recycle sludge flow, Q_r, is held constant.	Time of test short; variation in influent wastewater flow, Q_i, is negligible during test period; recycle sludge flow, Q_r, is held constant.
(3) Influent DO, C'_o, is constant	Time of test short; variations in influent wastewater flow, Q_i, and DO, C_i, are negligible during test period; recycle sludge flow, Q_r is held constant.	Time of test short; variations in influent wastewater flow, Q_i, and DO, C_i, are negligible during test period; recycle sludge flow, Q_r, is held constant.
(4) Aeration volume oxygen uptake rate, R, is constant	Time of test short; aeration volume biological solids, X, and recycle sludge flow, Q_r, remain constant; influent wastewater flow, Q_i, and carbonaceous substrate, S, variations are negligible during test period. (Note that R may be difficult to accurately determine for systems with high organic loadings. (Refer to test procedure discussion for details.)	Time of test short; aeration volume biological solids, X, and recycle sludge flow, Q_r, remain constant; influent wastewater flow, Q_i, and carbonaceous substrate, S, variations are negligible during test period. (Note that R may be difficult to accurately determine for systems with high organic loadings. (Refer to test procedure discussion for details.)
(5) Effective oxygen transfer rate, K_La_f, is constant	Time of test short; alpha, α, value remains constant during the test period.	Time of test short; alpha, α, value remains constant during the test period.

Let:

$$F_1 = R - \frac{Q'}{V}(C'_o - C_R) \tag{70}$$

Therefore:

$$K_La_f = \frac{F_1}{C^*_{\infty f} - C_R} \tag{71}$$

Steady State Batch Test

$$0 = Q_r(C_r - C_R) - VR + VK_La_f(C^*_{\infty f} - C_R) \tag{72}$$

Let:

$$B_1 = R - \frac{Q_r}{V}(C_r - C_R) \tag{73}$$

Therefore:

$$K_La_f = \frac{B_1}{C^*_{\infty f} - C_R} \tag{74}$$

Unsteady State Continuous Test

$$\frac{dC}{dt} = -R + \frac{Q'}{V}(C'_o - C) + K_La_f(C^*_{\infty f} - C) \tag{75}$$

Substitute Equation 71 into Equation 75 and rearrange to obtain Equation 76:

$$\frac{dC}{dt} = \left(K_La_f + \frac{Q'}{V}\right)(C_R - C) \tag{76}$$

with C at $t = 0$ equal to C_o.

Therefore:

$$(C_R - C) = (C_R - C_o)\exp-\left[\left(K_La_f + \frac{Q'}{V}\right)t\right] \tag{77}$$

Unsteady State Batch Test

$$\frac{dC}{dt} = -R + \frac{Q_r}{V}(C_r - C) + K_La_f(C^*_{\infty f} - C) \tag{78}$$

Substitute Equation 74 into Equation 78 and rearrange to obtain Equation 79:

$$\frac{dC}{dt} = \left(K_La_f + \frac{Q_r}{V}\right)(C_R - C) \tag{79}$$

with C at $t = o$ equal to C_o.

Therefore:

$$(C_R - C) = (C_R - C_o)\exp-\left[\left(K_La_F + \frac{Q_r}{V}\right)t\right] \tag{80}$$

Additional mass balances can be written on the reactor systems described in Figure 17. Specifically, the off-gas and tracer methods may be easily shown to be governed by:

Off-Gas Method

$$V_g\left(\frac{d\bar{p}_o}{dt}\right) = (Q_{ai}p_{oi} - Q_a\bar{p}_o) - VK_La_f(\beta\bar{H}p_o - C)\left(\frac{\bar{R}\ \bar{T}}{M}\right) \tag{81}$$

where:

$\bar{H}$ = Henry's Law constant, $mL^{-1}f^{-1}$

$\bar{R}$ = universal gas constant, $fL\ mol^{-1}\ T^{-1}$

$\bar{T}$ = absolute temperature of the gas, T

M = molecular weight of the gas, m/mol

For $\frac{d\bar{p}_o}{dt} = 0$ and $\bar{p}_o = p_o$, the governing equation results:

$$K_La_f = \frac{(Q_{ai}p_{oi} - Q_ap_o)M}{(\beta\bar{H}p_o - C_R)\ V\ \bar{R}\ \bar{T}} \tag{82}$$

Oxygen transfer efficiency may be calculated using off gas measurements based upon the following relationships:

$$OTE = \frac{O_2\ in - O_2\ out}{O_2\ in} \tag{83}$$

$$OTE = \frac{G_i(M_o/M_i)MR_{o/i} - G_i(M_o/M_i)MR_{og/i}}{G_i(M_o/M_i)MR_{o/i}} \tag{84}$$

and

$$OTE = \frac{MR_{o/i} - MR_{og/i}}{MR_{o/i}} \tag{85}$$

where:

G_i = mass rate of inerts, m/t

M_o = molecular weight of oxygen, m

M_i = molcecular weights of inerts, m

$MR_{o/i}$ = mole ratio of oxygen to inerts in feed air

$MR_{og/i}$ = mole ratio of oxygen to inerts in off gas

The mole ratios may be related to mole fractions, Y, as follow:

$$MR_{o/i} \text{ or } MR_{og/i} = \frac{Y}{1 - Y - Y_{CO_2} - Y_W} \tag{86}$$

where the mole fractions for both feed air and off gas may be specified.

This test method is suitable for use as described by Mueller et al.[1] for closed-vessel systems, such as those found in many oxygen-enriched applications. It is also finding application in open tank systems as well.

Tracer Method

The tracer method is identical for clean water and respiring system conditions since the tracer, $\bar{\tau}$, used is a conservative, non-reactive substance. For example, for a batch system with Q_r equal to zero, the governing equation is given by:

$$\frac{dT}{dt} = K_L a_f \bar{\tau} \tag{87}$$

with $\bar{\tau}$ at $t = 0$ known.

Because of the limited application of this method in aeration equipment evaluations, further mathematical details are not presented in this report. For a more detailed review of this subject, refer to detailed discussions by Neal.[2]

MEASUREMENTS IN THE FIELD

The successful evaluation of aeration equipment in situ involves careful measurements of several key parameters under full-scale operating conditions. A discussion of these measurements and their importance in field evaluations follows.

Dissolved Oxygen

An accurate measure of the DO concentration in an aeration volume is essential to any evaluation of aeration equipment. For in situ testing, direct-reading DO probes are the only practical means of measuring the DO concentration in mixed liquor suspended solids (MLSS) samples. Following proper calibration of the probes, considerable care and attention are required to assure continuous reliable results under field contitions.

Aeration testing may be carried out on an entire tank or an isolated mixing zone within a test volume. Typically, a minimum of three probes are used in field testing and, depending on the type of aeration system being tested, placement of the units in the test tank can be critical. For example, in aeration volumes with a relatively uniform DO concentration (e.g., well mixed with respect to DO), probes may be located in the tank without regard to aerator mixing pattern. However, for aeration volumes that are not well mixed with respect to DO, probes should be strategically placed around the specific flow pattern of the aeration device. Typical sampling locations for DO measurement for several types of aeration equipment are illustrated in Figure 18.

Depending on the specific application, many of the aeration devices shown in Figure 18 will not yield a uniform DO concentration in the tank under test conditions. In addition, the flow patterns shown in Figure 18 are typical but are not necessarily valid for all applications. Thus, it is important to establish a complete DO profile on the aeration system prior to testing. The DO profile will indicate the actual mixing characteristics of the test tank and allow proper placement of the DO probes. For further discussion on mixing and the effects of basin geometry on mixing, refer to Section 8.

During field testing of aeration systems, the DO concentration should not be the limiting factor in the biological reaction. For instance, the DO can become limiting at approximately 0.5 mg/ℓ for nitrifying activated sludge systems. Therefore, it is essential that the minimum DO be above 0.5 mg/ℓ and 1.5 mg/ℓ during testing of non-nitrifying and nitrifying activated sludge systems, respectively.

Oxygen Uptake Rate

A significant factor for evaluating aeration equipment in respiring systems is an accurate measurement of the MLSS oxygen uptake rate, R. Experience has shown that accurate measurement of the rapid oxygen uptakes created by high organic loads is virtually impossible. Ideally, the oxygen uptake rate measurements should be taken in situ or immediately at the point of sample collection. However, as a practical matter, a finite time period elapses prior to field measurements of this parameter. Since the oxygen uptake rate of a sample will vary as the available soluble substrate is oxidized, significant variations in the uptake rate may be observed for samples taken from moderately to highly loaded systems. The information presented in Figure 19 illustrates such a situation. Thus, caution is urged where oxygen uptake

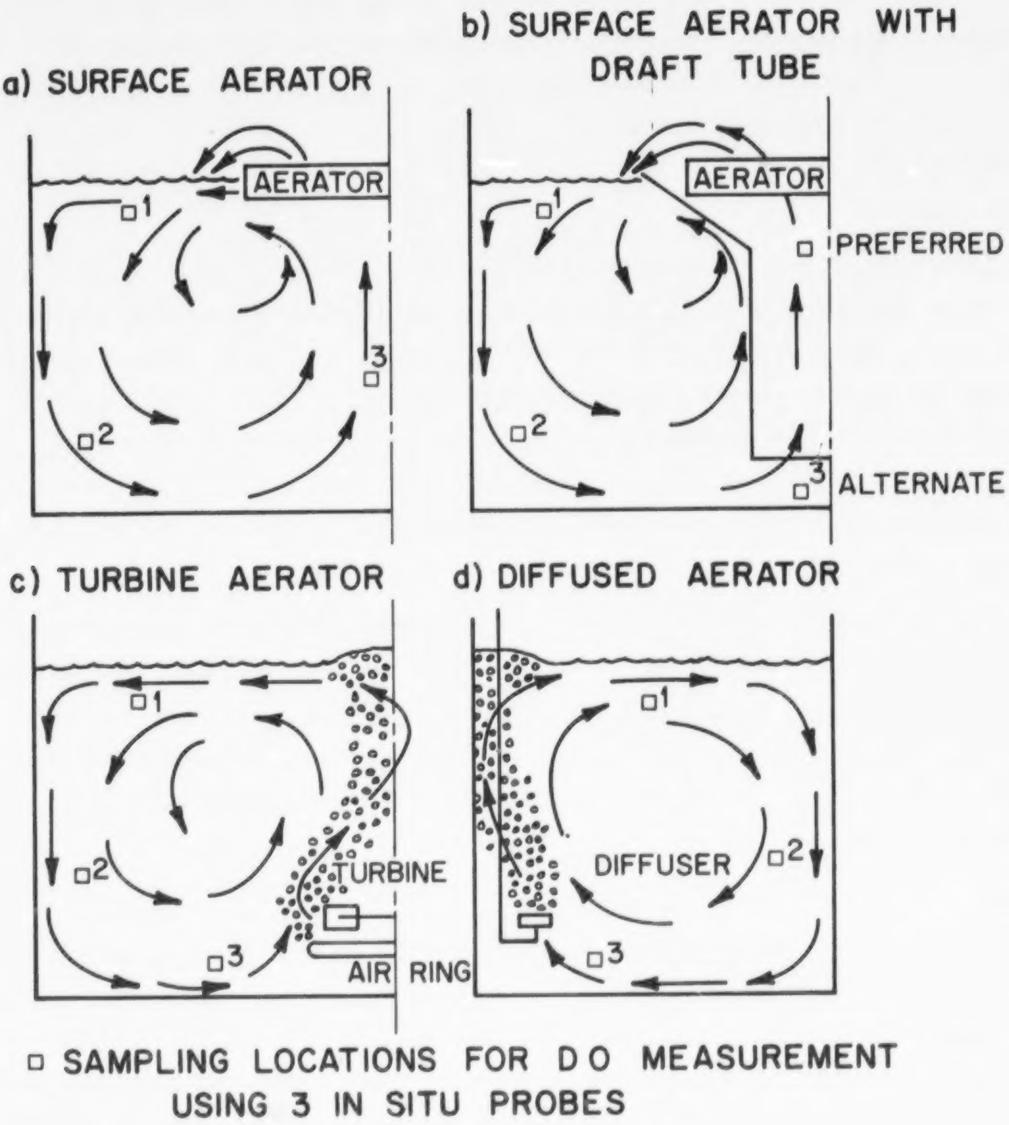
a) SURFACE AERATOR
AERATOR
1
2
3
b) SURFACE AERATOR WITH DRAFT TUBE
AERATOR
1
PREFERRED
2
3
ALTERNATE
c) TURBINE AERATOR
1
2
3
TURBINE
AIR RING
d) DIFFUSED AERATOR
1
DIFFUSER
2
3
□ SAMPLING LOCATIONS FOR D O MEASUREMENT
USING 3 IN SITU PROBES

Figure 18. Typical sampling locations for measurement of DO for different aeration systems.

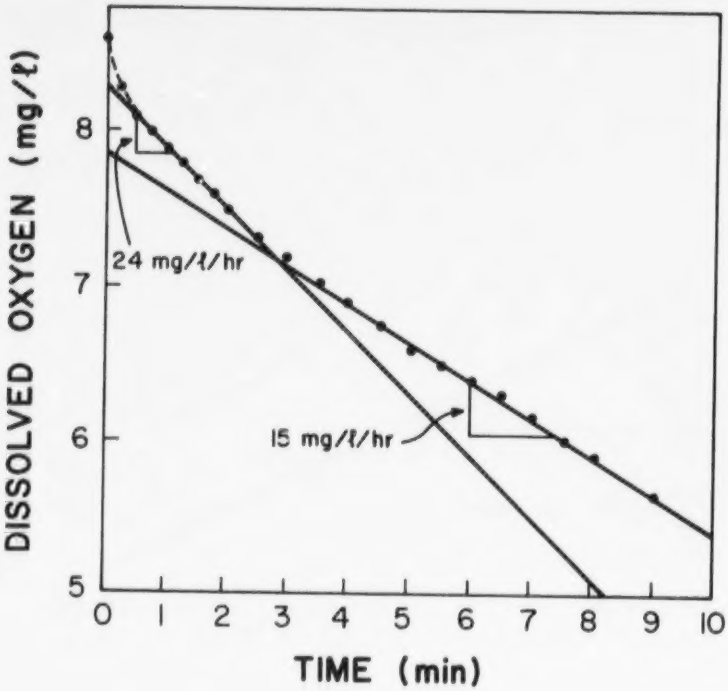

Figure 19. Oxygen uptake plot for steady state continuous testing in a moderately loaded activated sludge system.

rates are being measured under actual plant loading situations. One method used for estimating the actual oxygen uptake rate under these conditions is outlined in Appendix D.

A practical approach used to minimize the variability of the oxygen uptake rate is testing under endogenous respiration conditions. Endogenous respiration can be achieved by diverting the influent wastewater to other aeration tanks and allowing the MLSS to assimilate the remaining soluble organics. This procedure is the basis for batch testing and establishes a low and relatively constant oxygen uptake rate that can be more accurately measured. The data presented in Figure 20 illustrate the constant uptake rate obtained under endogenous conditions.

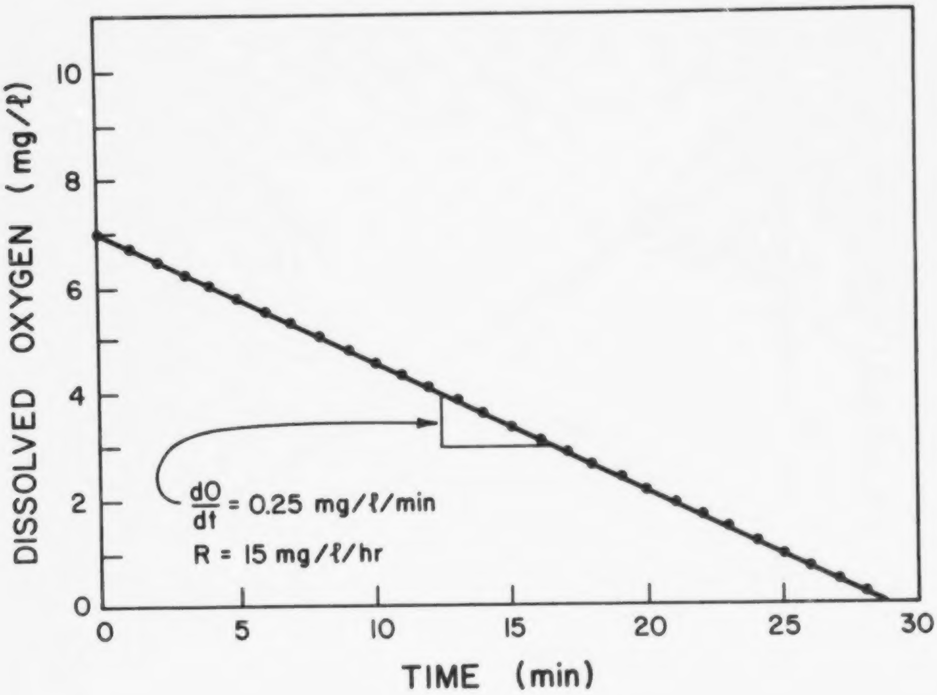

Figure 20. Oxygen uptake plot for steady state batch endogenous test.

Alpha and Beta Factors

Alpha, α, and beta, β, values are necessary for describing the influence of mixed liquor characteristics (e.g., dissolved substances and suspended solids) on the transfer capability of the aeration equipment in clean water. Generally, α and β measurements are made only when the field transfer rates are to be compared to standardized transfer rates developed under clean water conditions.

Due to the variability of influent wastewater quality, mixed liquor characteristics, and type of aeration device, the α level may be extremely variable for a given application. Testing under endogenous respiration conditions is advantageous because it tends to minimize the variability of α during the test period; however, the oxygen transfer rate obtained cannot be assumed to be the same as that occurring during operating conditions under normal plant loading. Since the subject area involving α and β corrections is rather complex, the reader should refer to Section 6 for a discussion of the factors affecting α and β and procedures for their determination.

Wastewater Temperature

Wastewater temperature also affects the evaluation of field oxygen transfer rates. Both oxygen transfer rate and oxygen uptake rate are significantly altered by changes in temperature. Biological reactions are thought to be governed by a doubling of rate for every 10°C increase in temperature [corresponds to $R_T = R_{20}\ 1.072^{(T-20)}$] within the practical operating range of 10-30°C.[3] Thus, if an oxygen uptake rate is measured at a wastewater temperature different from the actual operating temperature, the appropriate temperature correction for reaction rate must be made during data evaluation. At the same time, since aeration equipment is rated at 20°C, but is actually tested at some other temperature, appropriate transfer rate adjustments must also be applied to account for the effects of wastewater temperature. The temperature correction for oxygen transfer is discussed in detail in Section 6. Where practical, testing at temperatures near 20°C is desirable since it will minimize temperature corrections and allow a more accurate comparison with transfer rates at standard conditions.

TEST PROCEDURES

Steady State Testing

Test Descriptions--

Steady state testing involves simultaneous measurement of DO and oxygen uptake rates in full-scale aeration tanks. Testing may be conducted with or without influent wastewater flow to the aeration tank. For convenience, these testing methods are referred to as the continuous test (with wastewater flow) and the batch endogenous test (without wastewater flow).

The continuous test is the classical approach of determining field oxygen transfer in an aeration tank under normal operating conditions.[4,5,6,7] A general procedure for performing this test is as follows:

1. The liquid level in the aeration tank should be adjusted to the

desired power consumption of the aeration equipment. This liquid level should be recorded for future reference.

2. Initially, the DO concentration should be measured at points around the aeration tank (DO profile). The locations for measurement should be selected to define the mixing patterns for the system and to ensure that the entire test volume is aerobic. During the test, a minimum of three probes should be utilized for repeated DO measurements.
3. The DO concentration should be measured on both the influent and effluent flows of the test tank.
4. The oxygen uptake rates should be measured on the mixed liquor at the same time and at the same points that the routine DO measurements are made.
5. The air and mixed liquor temperatures should be measured at the same time as DO measurements are made.
6. The DO and oxygen uptake measurements should be repeated several times to obtain representative and reproducible values for the specified test period.
7. Measurement of the barometric pressure and determination of an α value (see Section 6) are required if correlation to standard conditions is desired.
8. A sample of mixed liquor should be analyzed for suspended solids to provide a MLSS concentration for reference purposes.
9. At the completion of the test, the DO probes should be recalibrated. If the recalibration indicates a significant deviation between the probe reading and calibration concentration (>5 percent), the instrument should be adjusted before further testing is initiated.

The batch endogenous test is conducted by discontinuing the influent wastewater flow to the aeration tank prior to the test period. The recycle sludge flow to the aeration tank may be held constant or discontinued during the test period. Operation in the endogenous phase should yield more uniform aeration tank contents (e.g., R, DO, and α value) and should result in increased testing accuracy. The following steps are necessary to bring the system to endogenous conditions:

1. The influent wastewater flow to the aeration tank must be discontinued. Recycle sludge flow may be discontinued or allowed to recycle normally to prevent septicity of the sludge in the secondary clarifier.
2. The liquid level in the aeration tank should be adjusted to produce the desired power consumption of the aeration equipment. This liquid level should be recorded for future reference.
3. The mixed liquor should be allowed to stabilize for a specified time period prior to the start of testing. Experience has shown that typically a period of 30 min to 2 hr is sufficient to bring the system to the endogenous respiration phase. Relatively constant values of DO and R at a given point, as determined by frequent measurements (say every 5 min) over a 30-min period, would indicate that steady state conditions had been reached.

After these steps are completed, the oxygen transfer rate may be determined following the continuous test procedure (Steps 2 through 9) previously outlined.

Data Evaluation--

The data obtained from the steady state tests may be evaluated using Equation 88 as described below:

$$K_L a_f = \frac{\text{System Test Constant}}{C^*_{\infty f} - C_R} \qquad (88)$$

where System Test Constant is:

Continuous Test

$$F_1 = R - \frac{Q'}{V}(C'_o - C_R) \qquad (70)$$

Batch Test

$$B_1 = R - \frac{Q_r}{V}(C_r - C_R) \text{ (with recycle sludge flow)} \qquad (73)$$

$$B_1 = R \text{ (without recycle sludge flow)} \qquad (89)$$

R = average oxygen uptake rate, $mL^{-3}t^{-1}$, of the MLSS in the test volume, V

Q' = influent flow, L^3/t, to the test volume, V

V = test volume, L^3

C'_o = DO level, m/L^3, in the test volume influent flow, Q'

C_R = DO level, m/L^3, that most accurately represents the driving force, $C^*_{\infty f} - C_R$, in the transfer zone of the system. For aeration systems that have a relatively uniform DO concentration (well mixed with respect to DO), C_R would be the average DO of the entire test volume, $\bar{C}_R$. For systems that are not well mixed with respect to DO concentrations (usually associated with continuous testing), C_R, equal to the DO level in the liquid as it flows to the aeration device ($\hat{C}_R$—see Points □ 3, Figure 18), has been shown to more closely approximate the actual system oxygen transfer rate.[8][†]

Q_r = recycle sludge flow, L^3/t, to the test volume, V

C_r = DO level, m/L^3, in the recycle sludge flow, Q_r

$C^*_{\infty f}$ = effective saturation DO level, m/L^3, at the test wastewater temperature. This value will vary depending on the type of aeration equipment tested and the aeration tank depth. For surface aeration equipment, the surface saturation DO level will closely approximate $C^*_{\infty f}$. For diffused aeration devices, $C^*_{\infty f}$ is unknown and must be determined through testing.

The resulting K_La_f represents the field oxygen transfer rate for the specified test temperature.

Example Calculations--

Continuous test results (hypothetical case)--Testing was conducted in a 1.0-mil gal aeration basin operating with four 40-hp floating surface aerators. Recyle of sludge to the basin was 33 percent of forward flow. Probes were positioned at four different locations in the basin that was receiving 1.5 mgd of industrial wastewater flow. Oxygen uptake rates and DO levels were measured every 20 min at each of these locations over a period of 2 hr. The average values for these parameters and test conditions are presented in Table 17.

[†] There is considerable controversy among Subcommittee members on this point. For example, Boon et al.[9] believe any value for C_R other than the average over the test volume would yield a "local value" of K_La_f and not the overall system transfer coeffient. They have reasoned that if the DO level is not constant throughout the tank (as previously assumed in development of the equations), then Equation 88 is not valid for evaluation of that aeration system. Furthermore, Boon[10] feels that the variation in DO concentration at any point in the aeration test volume compared to the mean value should not be greater than 10 percent of the deficit ($C^*_{\infty f} - C_R$) or the value of K_La_f would vary by more than 10 percent of its mean value.

The temperature of the mixed liquor during the oxygen uptake test was 19°C, necessitating correction downward to the 18°C operating temperature of the aeration basin. Thus, the average oxygen uptake rate at 18°C was 20.7 mg/ℓ/hr. The influent DO concentration, C_O', was 4.7 mg/ℓ. With the values of R, C_R (the oxygen content of the mixed liquor returning to the aerator when R was determined), C_∞^*, and β (as determined from Section 6), the value of K_La_f may be determined from Equations 88 and 70 as follows:

$Q' = Q_1 + Q_r = (1.5 \times 1.33)/24 = 0.083$ mil gal/hr

$\beta = 0.97$

$\overline{R} = 20.7$ mg/ℓ/hr

$C'_o = 4.7$ mg/ℓ

$C_\infty^* = 9.5$ mg/ℓ (book value of surface saturation at 18.0°C)

TABLE 17. TEST INFORMATION FOR CONTINUOUS TESTING OF A SURFACE AERATION SYSTEM*

Test Conditions

Aeration temperature = 18.0°C
β = 0.97 (determined as described in Section 6)
MLSS temperature during oxygen uptake testing = 19.0°C

Probe Location	R (mg/ℓ/hr)	C_R (mg/ℓ)
1	21.6	4.8
2	20.8	4.8
3	22.2	4.7
4	24.1	4.5
Average	22.2	4.7

*The value given for each probe location represents the average of six determinations over the 2-hr test period. A portion of the influent flows through a cooling tower so that the test volume influent DO concentation, C'_O, ranged between 4.5 and 5.0 mg/ℓ during the test period. Thus, the net change in oxygen in the liquid stream flowing through the aeration tank was negligible for the test period.

$$C^*_{\infty f} = \beta C^*_\infty = 0.97 \times 9.5 = 9.22 \text{ mg/}\ell$$
$$\overline{C}_R = 4.7 \text{ mg/}\ell$$
$$F_1 = 20.7 - (0.083/1.0)(4.7 - 4.7) = 20.7 \text{ mg/}\ell\text{/hr}$$
$$K_La_f = 20.7/(9.22 - 4.7) = 4.6 \text{ hr}^{-1}$$

Batch endogenous test results (hypothetical case)--Wastewater flow to a 1.0-mil gal aeration basin was discontinued for 2 hr prior to data collection. The DO and oxygen uptake rates remained essentially constant. Data were collected from three locations at 20 min intervals for 80 min (Table 18). Oxygen uptake data were collected at 19.5°C, thereby necessitating a correction in $\overline{R}$ down to 19°C. ($\overline{R}$ = 13.8 mg/l/hr at 19°C). With values of $\overline{R}$, $\overline{C}_R$, C^*_∞, and β the value of K_La_f may be calculated from Equations 88 and 89 as follows:

$$\beta = 0.97$$
$$\overline{R} = 13.8 \text{ mg/}\ell\text{/hr}$$
$$C^*_\infty = 9.3 \text{ mg/}\ell \text{ (book value of surface saturation 19.0°C)}$$
$$C^*_{\infty f} = \beta C^*_\infty = 0.97 \times 9.3 = 9.02 \text{ mg/}\ell$$
$$\overline{C}_R = 6.1 \text{ mg/}\ell$$
$$B_1 = \overline{R} = 13.8 \text{ mg/}\ell\text{/hr (without recycle sludge flow)}$$
$$K_La_f = 13.8/(9.02 - 6.1) = 4.7 \text{ hr}^{-1}$$

TABLE 18. TEST INFORMATION FOR BATCH TESTING OF A SURFACE AERATION SYSTEM*

Test Conditions

Aeration temperature = 19°C
β = 0.97 (determined as described in Section 6)
MLSS temperature during oxygen uptake testing = 19.5°C

Probe Location	R (mg/ℓ/hr)	C_R (mg/ℓ)
1	14.3	6.1
2	14.5	6.0
3	14.2	6.1
Average	14.3	6.1

*The value given for each probe location represents the average of six determinations over the 2-hr test period.

Testing Limitations--

The limitations of a specific test method must be recognized to ensure adequate data collection and allow an appreciation for the accuracy of the end result. For the steady state testing approaches, the following discussion outlines the specific test limitations that have been identified.

Continuous testing--An accurate determination of the value of R may be very difficult to obtain if system influent wastewater flow and substrate concentration are not constant during the test period.[7,11] In addition, if the system being tested has a high organic loading, the value of R will be nearly impossible to determine accurately. Appendix D outlines a method for approximating R under such continuous operating conditions, but even this approach is only a rough estimate. Thus, the accuracy of the $K_L a_f$ determination is directly tied to the ability to determine a representative value of R for the system. McKinney and Stukenberg[8] found that for R values greater than 60 mg/ℓ/hr errors in measurements can be significant and increase with increasing R values.

The inability to control the α value of the test volume during the test period may be a serious drawback to continuous testing. The α level may vary substantially (as much as ± 20 percent) at a given location within the tank during the test duration due to variable influent wastewater characteristics. In addition, the α level may even vary spatially within the tank at a given time during the test depending on the degree of treatment and system mixing patterns.

For many applications, specifically for surface aeration installations, the DO concentration may vary spatially within the tank at a given time during testing under continuous loading conditions. Therefore, the continuous testing approach may not be valid for those applications where such variation exists. Furthermore, if the variation in DO concentration at any point in the aeration test volume compared to the mean value is greater than ± 10 percent of the deficit ($C^*_{\infty f} - C_R$), then the resultant $K_L a_f$ should be considered no more accurate than this measured DO variability.

The requirement of maintaining the excess DO level, C_R, within a practical range during the test period may also be a limitation for some test applications. In order to define a reasonable range for accurate DO determination, the measured C_R level should be between a minimum of 2 mg/ℓ and a maximum of 75 percent of the system $C^*_{\infty f}$. Limiting the test conditions to this range will ensure the statistical validity of the DO measurement and provide a meaningful end result.

The inability to determine a $C^*_{\infty f}$ value for submerged aeration systems effectively limits the use of the continuous test. This technique may be used for submerged aeration systems only where it is possible to perform the test at a minimum of three different oxygen uptake rates. Different oxygen uptake rates may be established by varying the MLSS concentration under a constant organic loading rate or by varying the organic loading rate for a constant MLSS concentation. Once collected, the data should be plotted as shown in Figure 21 for the graphical determination of K_La_f and $\beta\ C^*_\infty$, i.e., $C^*_{\infty f}$. The field transfer rate is the slope of the straight line plot (3.9 hr^{-1}), and the effective system saturation level is the X-axis intercept (9.7 mg/ℓ).

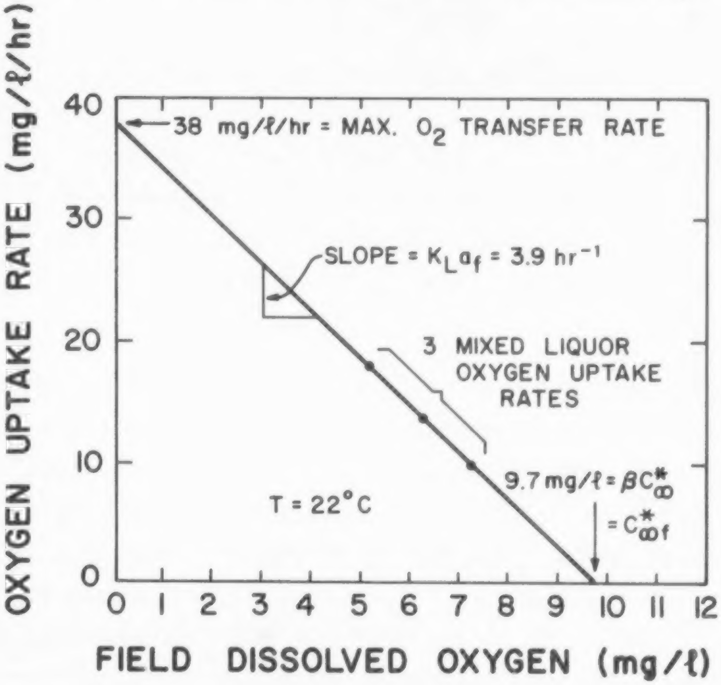

Figure 21. Steady state test results for submerged aeration evaluation.

Batch Testing--To achieve an endogenous respiration condition, the influent flow to the test volume must be discontinued. For systems with limited operational flexibility, this approach may not be practical.

When testing under endogenous respiration conditions, the α level would not necessarily reflect the α level at normal operating conditions. Therefore, if a field transfer rate under operating conditions is desired, the batch test may not yield an accurate estimation of that value. Depending on the specific application, testing under endogenous conditions would be expected to yield higher field transfer rates due to higher α levels. On the other hand, if the test is performed for comparison with a standard oxygen transfer rate, this approach should provide representative information for that comparison.

The requirement of maintaining the excess DO level, C_R, witnin a practical range during the test period may prove to be a limitation for some applications of the steady state batch test as with the steady state continuous test. In order to define a reasonable range for accurate DO determination, the measured C_R level should be between a minimum of 2 mg/ℓ and a maximum of 75 percent of the system $C^*_{\infty f}$. Limiting the test conditions to this range will ensure statistical validity of the DO measurement and provide a meaningful end result.

The inability to determine a $C^*_{\infty f}$ value for submerged aeration systems effectively restricts the use of the batch test approach to a limited number of applications (see discussion in previous subsection on continuous test limitations).

Unsteady State Testing

Test Descriptions--

Unsteady state testing involves reduction or discontinuation of aeration in the test tank. This allows biological action, through the oxygen uptake of the MLSS, to reduce the DO concentration in the test volume. (Note that the biological organisms are analogous in this respect to the sodium sulfate used in clean water testing.) After the DO level has been depressed sufficiently, aeration is increased or reintroduced to the test tank. By simultaneously monitoring the increase in DO level and the oxygen uptake rate, the field oxygen transfer rate may be determined using a classical reaeration approach (refer to Section 5). Testing may be conducted with or without influent flow to the aeration tank. As with steady state testing, these two methods are referred to as the continuous test (with wastewater flow) and the batch endogenous test (without wastewater flow).

The continuous test attempts to determine the field oxygen transfer in an aeration tank under normal process conditions.[7] A general procedure for performing this test is as follows:

1. The liquid level in the aeration tank should be adjusted to produce the desired power consumption of the aeration equipment. This liquid level should be recorded for future reference.
2. Initially, the DO concentration should be measured at several points around the aeration tank (DO profile). The locations for measurement should be selected to define the mixing patterns of the system and to ensure that the entire test volume is aerobic. For the test, a minimum of three calibrated DO probes should be installed strategically within the aerator mixing zone of influence (see Figure 17) for repeated DO measurement.
3. The DO concentration should be measured in both the influent and effluent flows of the test tank.
4. The test should be initiated by reducing or interrupting aeration in the test volume. (Note: The test should be conducted during operating periods when the influent flow and wastewater quality are most uniform. This provision will minimize variations in R, α, and β to allow more reproducible results.)
5. The DO concentration should be monitored continuously. When the DO concentration approaches 0.5 mg/ℓ at any probe, aeration should be increased or reintroduced to the test tank.
6. The increase in DO concentration should be recorded continuously. Simultaneously, oxygen uptake rates should be measured at the same locations where the DO probes are situated. As often as practical, the oxygen uptake should be measured until the system DO concentration stabilizes at a constant value, i.e., ± 0.1 mg/ℓ.

7. The system air flow (if appropriate), energy input, mixed liquor temperature, air temperature, and barometric pressure should be measured and recorded for each test.
8. Measurement of the barometric pressure and determination of an α value (see Section 6) are required if correlation to standard conditions is desired.
9. A sample of mixed liquor should be analyzed for suspended solids to provide an MLSS concentration for reference purposes.
10. At the completion of the test, the DO probes should be recalibrated. If the recalibration indicates a significant deviation between the probe reading and calibration concentration (>5 percent), the instrument should be adjusted before further testing is initiated.
11. Steps 4 through 10 should be repeated at least three times to obtain representative results for data analysis.

The batch endogenous test is conducted by discontinuing the influent wastewater flow to the aeration tank prior to the test. The recycle sludge flow to the aeration tank may be held constant or discontinued during the test period. Operation in the endogenous phase should yield more uniform aeration tank contents, e.g., R, DO, and α value, and should result in increased testing accuracy. The following steps are necessary to bring the system to the endogenous condition:

1. The influent wastewater flow to the aeration tank must be discontinued. Recycle sludge flow may be discontinued or allowed to recycle normally to prevent septicity of the sludge in the secondary clarifier.
2. The liquid level in the aeration tank should be adjusted to produce the desired power consumption of the aeration equipment. This liquid level should be recorded for future reference.
3. The mixed liquor should be allowed to stabilize for a specified time period prior to the start of testing. Experience has shown that typically a period of 30 min to 2 hr is sufficient to bring the system to the endogenous respiration phase. Relatively constant

values of DO and R at a given point, as determined by frequent measurements (say every 5 min) over a 30-min period, would indicate that steady state conditions had been reached.

After these steps are completed, the oxygen transfer rate may be determined following the continuous test procedure previously outlined (Steps 2 through 11).

A batch endogenous desorption test that is very similar to the unsteady state batch endogneous test has been proposed by Kayser.[12] Instead of starting the test at a very low DO concentration, the desorption test starts at a supersaturated DO level in the test solution. The premise of the test is that the rate of oxygen desorption is the same as the rate of oxygen transfer to the water. The initial high DO concentration is achieved by a slug addition of hydrogen peroxide uniformly distributed over the entire test volume. Following the initial peroxide addition, by simultaneously monitoring the decrease in the DO level and the oxygen uptake rate at the same test tank locations, the field oxygen transfer rate may be determined using a classical deaeration approach. Testing is usually conducted using the following procedure:

1. The influent wastewater flow to the aeration tank must be discontinued. Sludge recycle flow may be discontinued or allowed to recycle normally to prevent septicity of the sludge in the secondary clarifier.
2. The liquid level in the aeration tank should be adusted to produce the desired power consumption of the aeration equipment. This liquid level should be recorded for future reference.
3. The mixed liquor should be allowed to stabilize for a specified time period prior to the start of testing. Experience has shown that typically a period of 30 min. to 2 hr is sufficient to bring the system to the endogenous respiration phase. Relatively constant values of DO and R at a given point, as determined by frequent measurements (say every 5 min) over a 30-min period, would indicate that steady state conditions had been reached.
4. Initially, the DO concentration should be measured at several points

around the aeration tank (DO profile). The locations for measurement should be selected to define the mixing patterns of the system and to ensure that the entire test volume is aerobic. For the test, a minimum of three calibrated DO probes should be installed strategically within the aerator mixing zone of influence (see Figure 18) for repeated DO measurement.

5. When the oxygen uptake has stabilized, the hydrogen peroxide solution should be added. Peroxide solutions of 30 to 50 percent can be used without further dilution. While the aerators are running, the peroxide solution should be added within a period of 5 to 6 min or less. Even distribution of the peroxide over the whole test tank is required (see Appendix E for details of addition for various aeration devices). It is recommended that sufficient hydrogen peroxide be added to increase the DO by 12 to 15 mg/ℓ. In order to increase the DO by 15 mg/ℓ, a dosage of approximately 32 mg/ℓ as 100 percent H_2O_2 or ≈270 lb/mil gal is needed.

6. The decrease in DO concentration should be recorded continuously. Simultaneously, oxygen uptake rates should be measured at the same tank locations. As often as practical, the oxygen uptake rates should be measured until the system DO concentration stabilizes at a constant value, i.e., ± 0.1 mg/ℓ.

7. The system air flow (if appropriate), energy input, mixed liquor temperature, air temperature and barometric pressure should be measured and recorded for each test.

8. Measurement of the barometric pressure and determination of an α value (see Section 6) are required if correlation to standard condition is desired.

9. A sample of mixed liquor should be analyzed for suspended solids to provide an MLSS concentration for reference purposes.

10. At the completion of the test, the DO probes should be recalibrated. If the recalibration indicates a significant deviation between the probe reading and calibration concentration (>5 percent), the instrument should be adjusted before further testing is initiated.

11. Steps 5 through 10 should be repeated at least three times to obtain representative results for data analysis.

Data Evaluation--

The data obtained from the unsteady state test may be evaluated using Equation 90 as described below:

$$(C_R - C) = C_R - C_o)\exp-[(K_L a_f + \text{System Time Constant})t] \qquad (90)$$

where:

C = DO concentration, m/L^3, at any time, t

C_R = DO level, m/L^3, that most accurately represents the driving force, $C^*_{\infty f} - C_R$, in the transfer zone of the system. For aeration systems that have a relatively uniform DO concentration (well mixed with respect to DO), C_R would be the average DO of the entire test volume, $\overline{C}_R$. For systems that are not well mixed with respect to DO concentrations (usually associated with continuous testing), C_R, equal to the DO level in the liquid as it flows to the aeration device ($\hat{C}_R$ — see points □3, Figure 18), has been shown to more closely approximate the actual oxygen transfer rate.[8][*]

C_o = DO concentration at test time t = 0, m/L^3

System Time Constant is:

Continuous Test

$$\frac{Q'}{V}$$

Batch Test

$\frac{Q_r}{V}$ (with recycle sludge flow)

0 (without recycle sludge flow)

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[*] There is considerable controversy among Subcommittee members on this point. For example, Boon et al.[9] believe any value for C_R other than the average over the test volume would yield a "local value" of $K_L a_f$ and not the overall system transfer coefficient. They have reasoned that if the DO level is not constant throughout the tank (as previously assumed in development of the equations), then Equation 88 is not valid for evaluation of that aeration system. Furthermore, Boon[10] feels that the variation in DO concentration at any point in the aeration test volume compared to the mean value should not be greater than 10 percent of the deficit ($C^*_{\infty f} - C_R$) or the value of $K_L a_f$ would vary by more than 10 percent of its mean value.

Equation 90 is the same general form as the equation used for clean water evaluations. Therefore, the same evaluation techniques are applicable, except that for respiring systems the term (K_La_f + System Time Constant) is obtained where K_La would be determined for clean water testing. The appropriate methods of analysis involve a computer program solution or graphical solution and are described in detail in Section 4.

Once K_La_f has been determined, the corresponding effective field DO saturation concentration, C^*_f, can be calculated. This calculation may be performed utilizing Equation 91 as follows:

$$C^*_{\infty f} = C_R + \frac{R + (\text{System Time Constant})(C_R - C'_o)}{K_La_f} \qquad (91)$$

where:

C'_o = DO level in the combined wastewater influent and sludge recycle flow, Q', for continuous testing and DO level in the sludge recycle flow, Q_r, for batch testing

Example Calculations--

The description of test procedures indicates a minimum of three in situ probes is recommended for field test purposes. For the sake of simplicity, the examples that follow will review only calculations based upon the data set from one of the installed probes. The data from each probe should be analyzed independently so that the results may be averaged to obtain the field oxygen transfer value.

Continuous test results--The data from continuous testing of a diffused aeration system for an industrial application are presented in Table 19. The background information for the test is as follows:

T = 30°C

Q_i = 1.2 mgd

Q_r = 0.5 mgd

Q' = 1.7 mgd

C'_o = 0 mg/ℓ

V = 0.75 mil gal (19-ft liquid depth)

$\overline{R}$ = 30 mg/ℓ/hr (average of five results collected during the test period)

TABLE 19. UNSTEADY STATE CONTINUOUS TEST DATA

Time (min)	DO (mg/ℓ)	Time (min)	DO (mg/ℓ)
0	0.2	13	3.5
1	0.4	14	3.6
2	1.0	15	3.6
3	1.3	17	3.9
4	1.7	19	4.0
5	2.0	20	4.1
6	2.2	25	4.2
7	2.5	30	4.4
8	2.6	35	4.4
9	2.9	40	4.5
10	3.1	45	4.5
11	3.2	50	4.5
12	3.4	60	4.5

The test data are plotted in Figures 22 and 23. From Figure 22, the equilibrium DO concentration for the system oxygen uptake rate, C_R, is established at 4.5 mg/ℓ. Using this value, Figure 23 was generated and $K_L a_f$ was determined to be 6.9 hr^{-1}. The effective field saturation DO level, $C^*_{\infty f}$, is given by Equation 91 as calculated below:

$$C^*_{\infty f} = 4.5 + \frac{30 + \left[\frac{1.7}{24(0.75)}\right](4.5 - 0.0)}{6.9}$$

$$C^*_{\infty f} = 4.5 + [(30 + 0.425)/6.9]$$

$$\underline{C^*_{\infty f}} = 4.5 + 4.4 = \underline{8.9 \text{ mg/ℓ}}$$

Batch endogenous test results--The unsteady state batch endogenous test has been used by Muller et al.[13] to analyze oxygen transfer efficiency in a 72-mgd municipal treatment plant containing diffused aerators. Twenty-four hr prior to the test, flow was diverted around the aeration tanks being analyzed and aeration was maintained. Approximately 1 hr prior to the test, two butterfly valves controlling air flow to the aeration tank being tested were

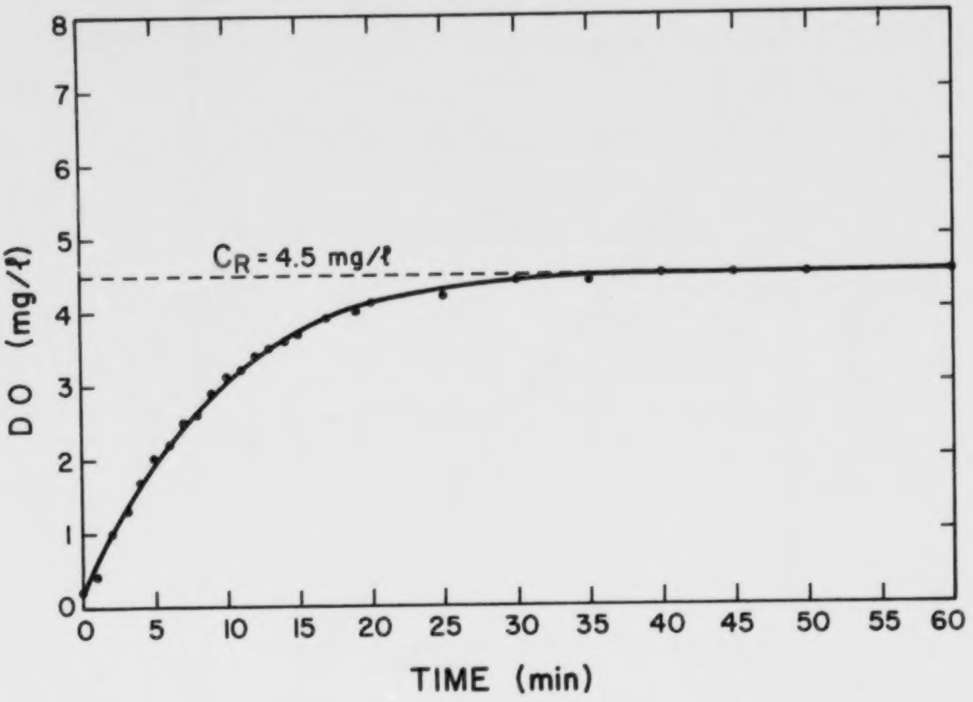

Figure 22. Unsteady state continuous test DO versus time plot.

throttled to approximately one-half the previous air flow, allowing the DO concentration to decrease but still maintaining solids in suspension. At the beginning of the test, air flow was increased and DO probe readings taken at the one-third points in four aeration bays. Air flow, temperature, and pressure readings for the two headers feeding the four bays were also taken along with oxygen uptake rates. The DO data taken at one point during the test are listed in Table 20 and plotted in Figures 24 and 25. The slope of the resulting line in Figure 25 is the K_La_f value of the aeration system, 4.2 hr^{-1}, at the test mixed liquor temperature. For the oxygen uptake value of 10.4 mg/ℓ/hr and a C_R value of 9.3 mg/ℓ, $C^*_{\infty f}$ was determined to be 12.0 mg/ℓ.

The above unsteady state batch endogenous data have also been analyzed using the nonlinear least squares technique and a computer program developed for clean water analysis. The results of this analysis are presented in Table 21. The oxygen transfer coefficient, K_La_f, was estimated at 4.05 hr^{-1} (0.0675 min^{-1}) and the C_R value as 9.4 mg/ℓ, both close to the values estimated from the semilog plot. The errors in these parameters are 2.66 percent

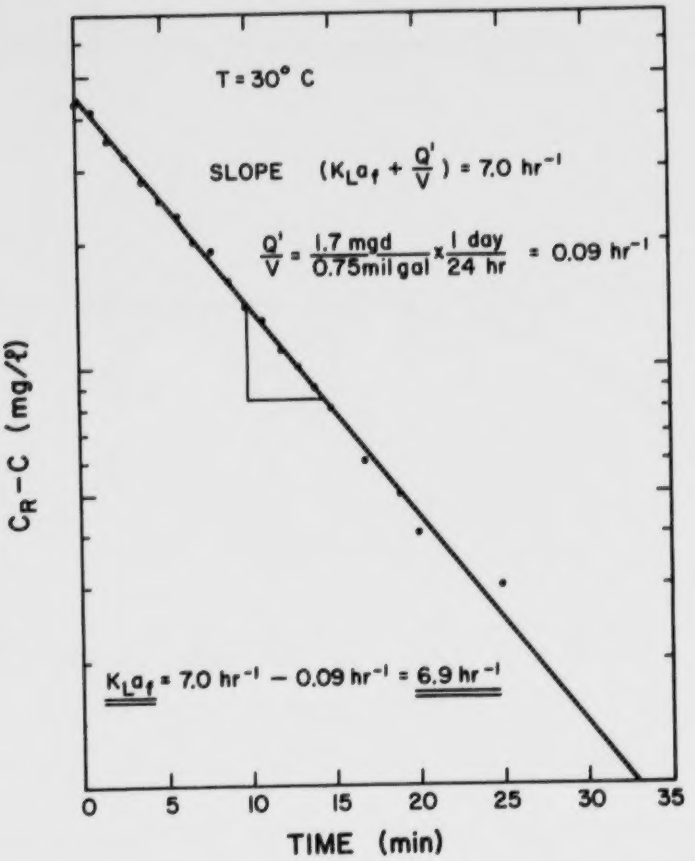

Figure 23. Unsteady state continuous test semilog plot.

and 0.92 percent, respectely, well within the acceptable error structure of 3 and 5 percent recommended as maximums for the clean water tests. The estimate of C_0 (the value of C at t = 0, estimated from the model) has a standard deviation of 0.055 mg/ℓ, also well within the acceptable value of 0.3 mg/ℓ recommended as a maximum for the clean water test.

Oxygen desorption test--The data from an unsteady state batch endogenous desorption test for a municipal diffused system are presented in Table 22. Sludge recycle flow to the system was discontinued during the test. The test was performed by Kayser[14] using a procedure similar to that outlined previously on pages 166-168. The background information for the test is as

TABLE 20. UNSTEADY STATE BATCH ENDOGENOUS TEST DATA

Test Conditions

Mixed liquor temperature = 12°C
Mixed liquor oxygen uptake rate = 10.4 mg/ℓ/hr
Mixed liquor steady state DO = 9.3 mg/ℓ

Time (min)	Mixed Liquor DO (mg/ℓ)	Time (min)	Mixed Liquor DO (mg/ℓ)
0.0	0.6	14.0	6.0
0.5	0.9	16.0	6.3
1.0	1.1	18.0	6.75
1.5	1.4	20.0	7.0
2.0	1.5	22.0	7.4
2.5	1.9	23.0	7.6
3.0	2.1	28.0	8.0
4.0	2.5	33.0	8.25
5.0	3.0	38.0	8.8
6.0	3.3	43.0	8.9
7.0	3.75	48.0	9.1
8.0	4.2	53.0	9.4
10.0	5.1	63.0	9.4
12.0	5.6		

follows:

T = 24°C

V = 0.43 mil gal (16.4-ft liquid depth)

$\overline{R}$ = 19.7 mg/ℓ/hr (average of six results collected during the test period)

The test data are plotted in Figures 26 and 27. From Figure 26, the equilibrium DO concentration for the system oxygen uptake rate, C_R, is established at 4.9 mg/ℓ. Using this value, Figure 27 was generated and $K_L a_f$ was determined to be 3.9 hr^{-1}. The effective field saturation level, $C^*_{\infty f}$, is given by Equation 91 as calculated below:

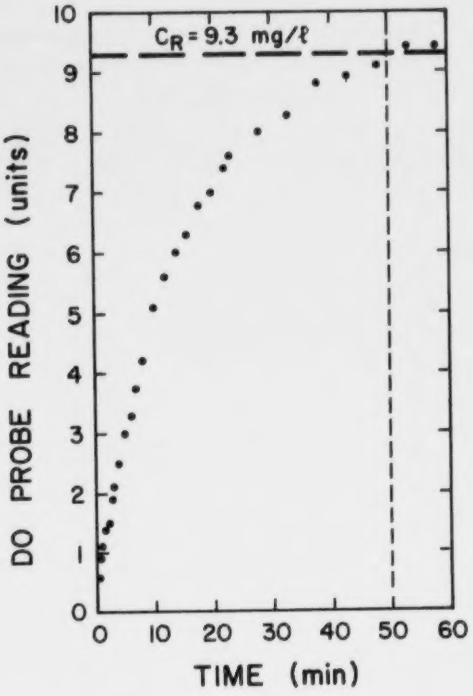

Figure 24. Unsteady state batch endogenous test plot of DO versus time.

$$C^*_{\infty f} = 4.9 + (19.7/3.9)$$

$$\underline{C^*_{\infty f}} = 4.9 + 5.1 = \underline{10.0\ \text{mg/ℓ}}$$

Test Limitations--

The limitations of a specific test method must be recognized to ensure adequate data collection and allow an appreciation for the accuracy of the end result. For the unsteady state testing approaches, the following discussion outlines the specific test limitations that have been identified.

Continuous testing--An accurate determination of the R value may be very difficult to obtain if influent flow and substrate concentration vary substantially during the test period. If either of these conditions exist, the reaeration curve may be erratic and the calculated $C^*_{\infty f}$ value, which is calculated using R, may be in error. As previously mentioned, a high organic loading to the test system ($R > 60$ mg/ℓ/hr) will also preclude an accurate measure-

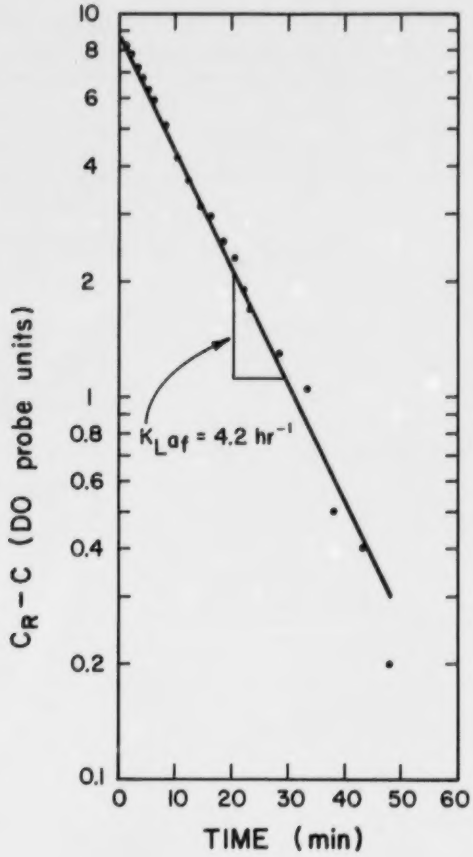

Figure 25. Unsteady state batch endogeneous test semilog plot.

ment of R.[8]

Due to the flow-through testing conditions, the influence of non-uniform influent wastewater flow and substrate concentration will cause variable system R and α values over the test period. In addition, under flow-through conditions, the maldistribution of the influent flow throughout the tank volume can bring about spatial variation of R and α values within the test volume. Therefore, testing should be conducted during operational periods when fluctuations in influent flow and organic strength are minimal.

For many applications, specifically for surface aeration installations, the DO concentration may vary spatially within the tank at a given time during testing under continuous loading conditions. Therefore, this test

TABLE 21. NONLINEAR ESTIMATION FOR UNSTEADY STATE OXYGEN TRANSFER DURING ENDOGENOUS TESTING

Input data in time, DO data pairs
Input 999,999 as last data pair

DATA SET

Iteration Number	C_R (mg/ℓ)	C_o (mg/ℓ)	K_La_f (min^{-1})	Sum of Squares
0	10	0.1	0.07	3.71155
1	9.39391	0.488792	0.0677646	0.234328
2	9.39667	0.488203	0.0675272	0.233152
3	9.39669	0.488197	0.0675274	0.233153

Standard Deviations of Parameter Estimates

Absolute Units	0.0866782	0.0554709	1.79764E-03
Percent of LSE	0.922437	11.3623	2.6621

Estimate of Error = 0.105368

SUMMARY OF DATA

Data Point	Time	Conc.	Fit Value	Residual
1	0.5	0.9	0.78396	.11604
2	1	1.1	1.0699	.0300967
3	1.5	1.4	1.34635	.0536465
4	2	1.5	1.61363	-.113625
5	2.5	1.9	1.87202	.0279769
6	3	2.1	2.12184	-.0218434
7	4	2.5	2.59688	-.0968757
8	5	3	3.04089	-.0408888
9	6	3.3	3.45591	-.15591
10	7	3.75	3.84383	-.0938306
11	8	4.2	4.20642	-6.42061E-03
12	10	5.1	4.86212	.237882
13	12	5.6	5.43498	.16502
14	14	6	5.93547	.0645294
15	16	6.3	6.37273	-.0727334
16	18	6.75	6.75476	-4.75597E-03
17	20	7	7.08852	-.0885172
18	22	7.4	7.38011	.0198865
19	23	7.6	7.51179	.0882082
20	28	8	8.0519	-.-519018
21	33	8.25	8.43725	-.187245
22	38	8.8	8.71217	.0878296
23	43	8.9	8.90832	-8.31795E-03
24	48	9.1	9.04826	.0517416

TABLE 22. UNSTEADY STATE BATCH OXYGEN DESORPTION TEST DATA

Time (min)	Mixed Liquor DO (mg/ℓ)	Time (min)	Mixed Liquor DO (mg/ℓ)
-7	4.8	9	15.0
-6	4.8	10	15.4
-5	6.2	12	13.1
-4	10.5	14	12.1
-3	15.0	16	11.5
-2	18.5	18	10.7
-1	21.5	20	10.0
0	23.5	25	8.7
1	22.6	30	7.7
2	22.2	35	7.0
3	21.0	40	6.4
4	19.5	50	5.6
5	18.1	60	5.3
6	17.2	70	5.1
7	16.2	80	4.9
8	15.6	90	4.9

approach may not be valid for those applications where such variation exists. Furthermore, if the variation in DO concentration at any point in the aeration test volume compared to the mean value is greater than ± 10 percent of the deficit ($C^*_{\infty f}$ - C_R), then the resultant K_La_f value should be considered no more accurate than this measured DO variability.

For systems with a low oxygen transfer rate and a high organic loading rate, the system equilibrium DO level, C_R, may be relatively low. To obtain sufficient test information for statistical data analysis, a reasonable range for the test parameter (C_R - C) is essential. Since the practical initial DO level will be approximately 0.5 mg/ℓ, a minimum C_R level of 4.0 mg/ℓ is recommended for reliable evaluation of test data. This provision may prohibit continuous testing at some installations.

For surface aeration installations, the only method of reducing the DO

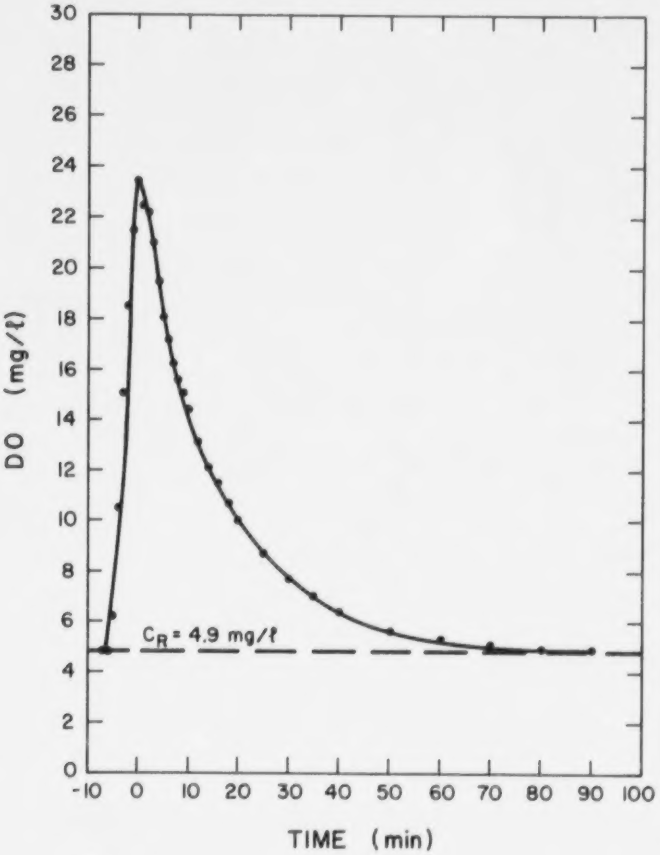

Figure 26. Unsteady state batch desorption test DO versus time plot.

concentration sufficiently may be to completely shut off the aerators or operate them intermittently. This action would result in inadequate mixing of the test volume, bringing about solids segregation during the deaeration phase of the testing. As the units are turned on for the reaeration phase of the testing, erratic results will be produced during the initial data collection period due to the re-establishment of the uniform mixing regime. Depending on the size and geometric configuration of the test volume, the effect of inadequate mixing could lead to erroneous test results.

Batch testing--To achieve an endogenous respiration condition, the influent flow to the test volume must be discontinued. For systems with limited operational flexibility, this approach may not be practical.

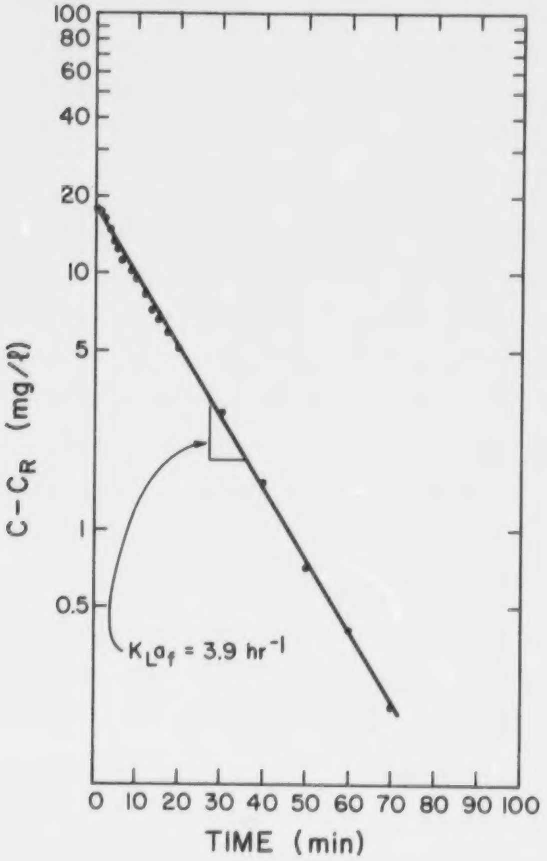

Figure 27. Unsteady state batch desorption test semilog plot.

When testing under endogenous respiration conditions, the α level would not necessarily reflect the α level at normal operating conditions. Therefore, if a field transfer rate under operating conditions is desired, the batch test may not yield an accurate estimation of that value. Depending on the specific application, testing under endogenous conditions would be expected to yield higher field transfer rates due to higher α levels. On the other hand, if the test is performed for comparison with a standard oxygen transfer rate, this approach should provide representative information for that comparison.

The requirement of maintaining the excess DO level, C_R, within a practical range during the test period may prove to be a limitation for some applications of the unsteady state batch test. In order to define a reasonable range for accurate DO determination, the measured C_R level should be between a minimum of 2 mg/ℓ and a maximum of 75 percent of the system $C^*_{\infty f}$. Limiting the test conditions to this range will ensure the statistical validity of the DO measurement and provide a meaningful end result.

For surface aeration installations, the only method of reducing the DO concentration sufficiently may be to completely shut off the aerators or operate them intermittently. This action would result in inadequate mixing of the test volume and bringing about solids segregation during the deaeration phase of the testing. As the units are turned on for the reaeration phase of the testing, erratic results will be produced during the initial data collection period due to the re-establishment of the uniform mixing regime. Depending on the size and geometric configuration of the test volume, the effect of inadequate mixing could lead to erroneous test results.

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This method assumes that the hydrogen peroxide immediately and fully disassociates to DO and water when added to the test volume. In addition, this approach is based on the premise that the rate of oxygen desorption from water to air is the same rate as oxygen transfer from air to water. Kayser's work[14] seems to verify both of these assumptions. However, if the peroxide does not fully disassociate before the start of the test, the resulting oxygen transfer rate determination will be erroneously lower than the actual field transfer rate.

Other Test Approaches

In addition to the above tests, other procedures may also be employed to evaluate aeration systems used in biological treatment. For the most part, these procedures have not been extensively used and, therefore, cannot be recommended as primary tests for respiring system field tests. However, these tests may have application for specific treatment operations.

Mass Balance: Activated Sludge Systems--

The mass balance approach has been proposed to determine oxygen transfer in operational activated sludge systems. Total oxygen balances must be made on the influent, effluent, and waste activated sludge. The change in total oxygen across the entire activated sludge system equals the oxygen transferred by the aeration system. Total oxygen measurements should be based on COD, with correction for nitrification. The major problems with the mass balance technique lie in satisfactory measurement of waste activated sludge volumes and in obtaining representative samples of waste activated sludge for analysis. The high suspended solids concentrations in waste activated sludge make it difficult to obtain valid data because of large errors that can result from minor variations in the aeration volume solids inventory. While it is possible to achieve accurate mass balance measurements on small laboratory systems, this technique has limited practical value in field-scale evaluation of aeration equipment for activated sludge systems.

Mass balances have been used with some degree of success with well-mixed activated sludge systems.[15] Short detention time systems with sufficient power to keep all of the solids in suspension can be evaluated by measuring the difference between the influent and effluent COD concentrations (including the COD of the waste sludge) over a period of time equal to at least six times the system hydraulic retention time. With this provision, variations in waste characteristics can be leveled out to yield more representative data. In most cases, analysis of data over a 1-mo period should provide reasonable correlation for evaluation of the aeration equipment.

In the mass balance evaluation, care must be taken to ensure that the aeration system is well mixed. If suspended solids settle out in the aeration tank, the data will indicate a higher oxygen transfer than is actually occurring. Furthermore, higher transfer rates can also be predicted for certain industrial wastewaters where volatilization of organic compounds occur during the aeration process. Therefore, if this technique is to be used in field evaluations, a careful review of the potential impact of aeration tank volatilization and solids deposition is recommended.

Mass Balance: Aerated Stabilization Basin Systems--

The mass balance procedure has been applied to low-rate aerated stabilization basin (ASB) systems because oxygen transfer cannot be readily measured using more direct methods. The accuracy of this method depends on the extent to which all factors that supply and withdraw oxygen from the system are measured. A number of these factors can be minimized during the test period so that the main factor that determines the aerator oxygen transfer is the reduction in BOD through the respiring system. The mass balance method is simple and straightforward, especially when the ASB system is aerator (oxygen) limited and where signficant settleable biological solids are not produced.[16]

Minimum DO procedure--In order to minimize or eliminate a correction factor for the working DO in the basin, turning off or redeploying aerators may be necessary if the system normally carries excess DO. Actually, several tests at approximately 60, 80, and 100 percent of tuned aeration capacity may be performed to ensure an accurate test. If the system is oxygen limited, the aeration efficiency (lb O_2/hp-day or kg/kWh) should be equal for each test. If the values don't agree, other limitations may exist, such as insufficient nutrients or the presence of toxic materials.

Certain systems will lend themselves to segregation for the purpose of testing. Basins in series or long narrow basins would be candidates for testing of various groupings of aerators. Thus, it is possible that tests could be made on various portions of the system at the same time and represent varying fractions of the tuned capacity. All portions of each cluster would have to be oxygen limited. The last stages of such a system might be omitted to improve the accuracy of the test procedure because these later stages are apt to produce excess DO during a portion of the test period.

The major variables in the calculation are the incoming and exiting masses of oxygen demanding materials. COD, TOC (converted to its oxygen equivalent), and ultimate BOD are the appropriate parameters around which to construct the balance. In certain cases, such as with many pulp and paper mill works, the BOD_5 can be used because the system removes only a small fraction of the COD[16,17] The calculation determines the difference between influent and effluent oxygen demand during the test period. This difference is then divided by the operating power used by the aerators during the same period. The calculation produces results in terms of lb oxygen transferred/hp-day (or kg/kWh).

It should be recognized that under oxygen-limited conditions there is a potential to accumulate BOD in the microbial mass that may result in an apparent oxygen transfer rate, OTR, greater than the actual OTR. However, because most ASB systems are respiring at extremely low rates, synthesis effects are minimal and can be neglected.

There are several other adjustments that can be incorporated into the calculation. A discussion of each follows:

DO difference--If the system has been properly tuned, the DO concentration returning to the inlet to the aeration device should be zero and the DO concentration leaving the basin will probably be zero. Thus, the case reduces to the situation where the incoming wastewater contains DO that would have to be debited from the aerator transfer. For most tuned situations, this factor represents less than 1 percent of the total transfer.

Surface area--This factor is usually disregarded. However, the aerators could be debited with a value of 50 lb O_2/acre of surface/day. This value represents BOD_5 removal associated with treatment in unaerated stabilization basins.[18] Unless the ASB is very large in comparison to the power combined in the aerators (i.e., greater than 10^6 gal/hp), the contribution of the surface area to aeration is not a major factor.

Benthal oxygen demand--Aerated stabilization basins are not completely aerobic. However, the pumping rate of the mechanical or diffused aerators recirculates the total basin contents through the aerobic zone to an extent that impedes the development of highly reduced conditions. Thus, appreciable amounts of oxygen are not required to satisfy an immediate chemical oxygen demand. However, bottom deposits, no matter how thin, constitute a continued sink for any oxygen that reaches the bottom. Sediment oxygen demand studies on a variety of benthal deposits have shown uptake rates varying from 1.0-20.0 $gm/m^2/day$. A credit of 5.5 $gm/m^2/day$ (50 lb/acre/day) is suggested for the benthal oxygen demand.[19,20,21] Again, even if DO exists near the bottom of most of the basin, the amount of oxygen removed is minimal.

Nitrification-denitrification factor--The oxygen equivalent of the nitrogen balance will have to be considered in some systems. The aerators should be credited with transferring the oxygen necessary to balance the change in the oxidative state of the nitrogen species entering and exiting the system. However, for all practical purposes, nitrification is suppressed under oxygen-limited conditions (e.g., DO less than 1.0 mg/ℓ) and also ceases at BOD_5:N ratios of 16 or higher.[22] Thus, nitrification and denitrification aren't significant in the oxygen-limited equilibrium test case and the high BOD_5:N case.

Correcting for temperature--One major advantage of using the mass balance approach is that no temperature correction is required. Biological kinetics predict a doubling of the reaction rate with each 10°C rise in temperature (i.e., $\theta = 1.072$).[23,24,25] Thus, an oxygen-limited system operating at 10°C would simply require less oxygen (hp) than when operated at 20°C. The oxygen demand would be matched only to the extent that there was aeration capacity in the system.

The oxygen transfer rate constant, K_La, is temperature dependent. The θ value most commonly used is 1.024. This θ value effectively offsets the temperature coefficient for the saturation concentration of DO in water. As an example, when DO is limited (i.e., DO = 0), the deficit equals the saturation concentration. The result is that approximately the same mass rate of oxygen is transferred into water at 10°C, at 20°C, and at 30°C under the oxygen-limited condition.

Excess DO procedure--Some ASB systems can't be turned down to minimize DO throughout the basin. Several additional factors must be considered to compute the oxygen transferred by the aeration equipment when excess DO is present in the basin. These factors are briefly reviewed as follows:

Driving force factor--If the basin is tested when excess DO is present, the aeration equipment isn't operating at maximum efficiency. Thus, a mass balance based on BOD removal won't account for the potential transfer that would occur had the test been performed at zero DO. In order to compute the potential transfer, it is necessary to determine β and the average DO in the basin. The average DO, $\overline{C}_R$, can be determined by testing representative volumes of the basin during the test period. Beta will have to be measured using the procedures prescribed elsewhere in this report. The potential BOD removal can then be increased by the ratio of the oxygen solubility to the oxygen deficit that exists during the test. In order to calculate the credit, a sampling program will have to be developed based on the temperal variation in DO at various points in the basin. Daily sampling at key locations in the basin may be required, especially if the BOD load to the basin fluctuates markedly. In systems where the photosynthetic addition of DO is a factor, the mass balance may have to be determined on an hourly basis to properly proportion the excess DO to the aeration system. Plug flow systems should be segmented volumetrically and weighted using the $C^*_{\infty f}$ and $\overline{C}_R$ values associated with each segment.

Temperature correction--The effect of temperature on the oxygen transfer rate will be included in the average DO concentration in the basin. Again, this factor is offset in the calculation for the maximum oxygen transfer rate at zero DO by the temperature coefficient for the saturation concentration, provided $\theta = 1.024$. Therefore, a temperature correction is not required.

Photosynthetic factor--Systems exhibiting photosynthesis represent a special case in the excess DO consideration. First, the variation in DO concentration in the basin will be a function of the availability of sunlight and will necessitate more frequent sampling for determining DO concentrations in the basin. Second, the contribution of DO by the algae will have to be debited from the aerator transfer should there be periods when DO becomes limiting in the system. During this time, BOD removal will utilize the added oxygen.

A large population of algae in an aerated basin will probably ensure that DO exists at most times in the basin. Thus, the only complication is debiting the oxygen contributed by the algae from the driving force factor. Light and dark bottle oxygen uptake rates could determine the mass of oxygen converted by the algae. This oxygen mass would then be equated to an equivalent DO concentration and subtracted from $\overline{C}_R$ so that the aeration potential isn't overestimated. Again, this is a very special case for the mass balance procedure and hasn't been applied as a means of computing the oxygen transfer of an aeration system.

Nitrification-denitification factor--Because excess DO is present in the system, nitrification is expected to proceed in systems receiving significant quantities of influent nitrogen. In activated sludge systems treating municipal wastewater, nitrogen oxidation may account for 5 to 25 percent of the total oxygen demand. Thus, it is reasonable to expect the change in the nitrogen oxygen demand (NOD) across the long-term system may be signficant where BOD_5:N ratios are less than 16:1 in the influent.

Equations for ASB mass transfer procedures[†]--

Minimum DO procedure--

$$OTR_{obs} = \sum_{j=1}^{j=n} \left[(BOD_r)_j + (NOD_r)_j \right] \qquad (92)$$

$$OTR_{act} = OTR_{obs} - \sum_{j=1}^{j=n} (8.34Q'C'_o)_j \pm \text{Accumulation Factor}^{\ddagger} \qquad (93)$$

$$AE = \frac{OTR_{act}}{\sum_{j=1}^{j=n} P_j} \qquad (94)$$

Excess DO procedure--

$$OTR_{cap} = \sum_{j=1}^{j=n} \left[(BOD_r)_j + (NOD_r)_j \right] \left[\frac{\beta\, C^*_{\infty T}}{C^*_{\infty T} - \overline{C}_T} \right]_j \qquad (95)$$

[†] The nomenclature used for ASB systems is slightly different that that used in the discussion of activated sludge testing. Therefore, the equivalent activated sludge nomenclature has been indicated with the ASB nomenclature, where appropriate

[‡] Accumulation factor is used to account for buildup or loss of BOD, DO, and NOD in the basin during the test period (see example).

$$OTR_{act} = OTR_{cap} - \sum_{j=1}^{j=n} 8.340Q'(C'_o - C_e)_j \pm \text{Accumulation Factor}^{\ddagger} \quad (96)$$

where:

OTR_{obs} = observed oxygen transfer rate accounting for the major variables (lb), m

OTR_{act} = actual oxygen transfer rate accounting for minor variables as well (lb), m

AE = aeration efficiency (lb O_2/hp-day), m $L^{-1}f^{-1}$

OTR_{cap} = oxygen transfer capacity had the system been operating under oxygen limiting conditions (lb), m

BOD_r = the ultimate BOD removed from the system, $S_i - S$ (lb), m

NOD_r = the oxygen equivalent of the nitrogen oxidation that takes place in the system, $f(N_i - N)$, where f is the appropriate conversion factor to units of oxygen (lb), m

C = dissolved oxygen concentration (mg/ℓ) (C'_o = influent, C_e = effluent, $\overline{C}_T$ = average at temperature T), m/L^3

Q' = flow into the basin (mgd), L^3/t

P = operating aerator power (hp-day), Lf/t

n = total number of sampling intervals

Example calculation for minimum DO case--A 5-day completely mixed ASB system was operated under oxygen limiting conditions for two periods during the month of October 1978. DO and settleable solids measurements were conducted at several points in the basin each day during the test period. The DO concentration was zero in water entering the aeration zone, and no settleable solids were produced. The basin was operated in a turned-down mode during the second half of the month. The liquid level in the basin remained constant during the test period. The performance data for the system are summarized in Table 23.

The data for the first 16 days and the last 11 days were analyzed as follows:

Parameter	October 1-16	October 20-31
Total BOD_5 reduction (lb)	1,147,110	724,500
Total operating power (hp-day)	27,950	18,230

The mass balance considerations are computed as follows:

TABLE 23. EXTERNAL WASTEWATER MANAGEMENT PROCESS PERFORMANCE DATA*

	Influent to Basin					Effluent from Basin			
Date	Flow (mgd)	Power (hp)	BOD$_5$ (mg/ℓ)	BOD$_5$ (1000 lb/day)	Suspended Solids (1000 lb/day)	Temp. (°C)	BOD$_5$ (1000 lb/day)	Suspended Solids (1000 lb/day)	BOD$_5$ Removal (%)
1	21.6	1800	521	9.40	24.5	30.5	11.1	19.5	88
2	20.5	1800	438	74.8	47.5	30.0	14.3	25.5	81
3	21.2	1800	540	95.4	21.4	30.0	16.7	15.2	82
4	20.0	1700	750	129.5	36.4	30.0	15.3	14.9	88
5	20.7	1675	456	78.8	22.6	30.5	18.4	15.8	77
6	20.2	1800	478	80.7	29.5	31.1	18.0	9.3	78
7	20.2	1800	501	84.6	26.2	28.8	23.6	17.2	72
8	19.8	1800	591	97.4	23.1	28.8	13.5	18.2	86
9	20.5	1800	427	72.9	27.3	28.3	14.4	18.7	80
10	20.7	1780	573	99.0	20.6	29.4	10.4	14.2	90
11	20.7	1675	485	83.8	30.7	29.4	9.0	19.9	89
12	20.0	1700	434	72.4	19.4	20.0	13.7	23.9	81
13	20.9	1640	435	76.0	15.5	30.5	9.7	13.7	87
14	21.4	1700	630	112.5	20.5	28.3	28.9	16.2	74
15	21.0	1700	459	80.4	16.5	28.3	29.6	18.1	63
16	21.4	1780	495	88.4	14.1	28.8	26.8	20.9	70
17	21.2	1640	368	65.0	24.6	27.7	21.4	15.9	67
18	21.3	1500	435	77.1	33.2	26.6	13.2	22.7	83
19	24.1	1460	336	67.5	29.5	26.6	17.6	22.7	74

(continued)

TABLE 23. (continued)

Influent to Basin						Effluent from Basin			
Date	Flow (mgd)	Power (hp)	BOD_5 (mg/ℓ)	BOD_5 (1000 lb/day)	Suspended Solids (1000 lb/day)	Temp. (°C)	BOD_5 (1000 lb/day)	Suspended Solids (1000 lb/day)	BOD_5 Removal (%)
20	23.1	1510	433	83.5	15.6	26.6	23.5	21.5	72
21	21.9	1640	485	88.5	21.0	27.7	33.3	13.7	62
22	24.1	1640	600	120.5	21.9	28.3	16.2	16.0	87
23	22.6	1530	383	72.2	16.2	28.3	10.3	4.4	86
24	22.1	1500	464	85.6	23.4	28.8	36.3	12.0	58
25	21.2	1500	513	90.6	19.6	28.8	24.8	13.5	73
26	21.4	1500	268	47.9	19.1	29.4	18.6	16.1	61
27	20.9	1500	298	52.1	27.4	30.0	14.4	15.2	72
28	22.6	1475	393	74.1	21.1	30.0	13.3	14.3	82
29	18.6	1500	600	93.2	19.6	29.4	15.3	11.5	84
30	20.0	1475	471	78.7	19.4	27.7	15.3	3.5	81
21	22.1	1460	403	74.3	86.5	27.2	15.4	19.8	81
Mean	21.3		473	83.6	25.6	28.9	18.2	16.3	78
Max	24.1		750	129.5	86.5	31.1	36.3	25.5	90
Min	18.6		268	47.9	14.1	26.6	9.0	3.5	58

*For month of October 1978.

DO difference--The average DO concentration in the flow entering the basin was 1.5 mg/ℓ. The DO concentration in the flow leaving the basin was 0.0 mg/ℓ. The system is debited with 270 lb O_2/day [(1.5 mg/ℓ) × (21.3 mgd) × (8.34)].

Surface area--The basin is 30 acres in area. This area would absorb 1500 lb of oxygen daily at an estimated rate of 50 lb/acre/day. This is a debit aeration calculation.

BOD accumulation--The BOD_5 concentration in the basin on October 1 was 62 mg/ℓ. The BOD_5 concentration in the basin on October 16 was 157 mg/ℓ. The system accumulated 83,000 lb of BOD_5 during the period of October 1-16 [(157 mg/ℓ - 62 mg/ℓ) × (8.34) × (105 mil gal)]. This is a debit in the aeration calculation. The BOD_5 concentration in the basin on October 20 was 122 mg/ℓ and by October 31 had dropped to 84 mg/ℓ. The system lost 33,400 lb during the period of October 20-31 [(122 mg/ℓ - 84 mg/ℓ) × (8.34) × (105 mil gal)]. This is a credit in the aeration calculation. In this case, which deals with paper mill waste, the BOD_5 difference is equivalent to the COD difference and, thus, is also equivalent to the actual oxygen consumed.

Anaerobic factor--The sediment oxygen demand is estimated at 50 lb/acre/day. This calculation is the same as the surface area calculation, only it becomes a credit in the mass balance consideration. The daily credit is 1500 lb of oxygen.

The total mass balance in this example is:

Parameter	October 1-16	October 20-31
BOD_5 reduction (lb)	1,147,110	724,500
DO difference (lb)	+4,320	+2,970
Surface area (lb)	-24,000	-16,500
Accumulation (lb)	-83,000	+33,400
Anaerobic factor (lb)	+24,000	+16,500
Total balance (lb)	1,068,430	760,870
Aeration efficiency (lb/hp-day)	38.2	41.6
Difference in aeration efficiency between periods (lb/hp-day)		3.4
Average aeration efficiency (lb/hp-day)		39.9

The average aeration efficiency would have been computed at 40.3 lb/hp-day if just the BOD_5 reduction values had been used. The accumulation factors could be further reduced by lengthening the test periods.

Limitations--The mass balance method cannot be applied in all cases. The accuracy of test results using this method depends on the extent to which all factors affecting the supply of oxygen to and depletion of oxygen from the system can be identified and quantified.

The test period should be long enough to reduce effects of short-term fluctuations in load, performance, and weather. To overcome this limitation, it is recommended that a period equal to three theoretical detention times, V/Q', be used for averaging the data.

The procedure assumes that the system is at equilibrium during the test period. Thus, the system should not be accumulating or releasing BOD that cannot be readily accounted for. The loss of settleable solids may be a sink for BOD in certain systems. Thus, the method is limited to systems where the mixed liquor contains less than 0.1 ml/ℓ settleable solids throughout the test period.

The mass balance method has not been employed in photosynthetically active aerated lagoon systems for the purposes of computing aeration oxygen transfer. This application requires further study.

Off-Gas Analysis--

Off-gas analysis has been used with full-scale, diffused aeration activated sludge systems and covered tank, pure oxygen activated sludge systems.[26] A mass balance on oxygen in the gas phase is required; therefore, this method is not applicable to surface aeration equipment. For systems that are not enclosed, a collector or hood is placed in the zone of interest in the aeration tank so a representative sample can be collected and analyzed for residual oxygen. As with the other methods, the validity of this technique depends on the accuracy and precision of the various parameters that have to be measured. For low efficiency of oxygen transfer (3 to 5 percent) associated with many diffused aeration systems, obtaining the requisite accuracy and precision of the mass balance on the input and discharge gases is difficult under the best of conditions. However, it is recognized that significant advances have been made in the recent past regarding instruments and techniques for measuring gas-phase oxygen concentration and aeration systems with oxygen transfer efficiencies of about 10 percent are becoming more the rule than the exception. The combined effect of these developments suggests the desirability of additional investigation of the utility and merit of this method. Recent efforts to develop off-gas techniques that will provide the requisite accuracy and precision in field situations have been reported.[27,28,29]

Tracer Method--

A radioactive tracer technique has been proposed to measure oxygen transfer rates in any aeration system, either in clear water or in wastewater.[2] The tracer method requires considerable planning, special radioactive counting equipment, and a radioactive materials license to use the radioisotopes, krypton-85 and tritium. The basic concept of the radioactive tracer technique involves direct measurement of the mass transfer of krypton-85, which is related to the oxygen transfer rate. The tritium is used to measure the dispersion of the tracers in the aeration tank. Both tracers are added to the aeration tank at a single point. As the tracers are dispersed in the aeration tank, the tritium mixes with the mixed liquor while the krypton-85 is stripped off in the gas phase. The key to this procedure lies in the fact that the krypton-85 stripping rate from the mixed liquor is directly related to the oxygen transfer rate from the gas into the mixed liquor. In effect, the tracer method is an indirect method for measuring oxygen transfer. A series of grab samples are collected and counted in a scintillation counter. Care must be taken to ensure that gas bubbles do not form in the samples as the krypton-85 would come to equilibrium with the gas bubbles and produce an error in the radioactive counts. Accurate counting of the samples is essential for obtaining good results. The counting efficiency is about 30 percent for tritium and about 90 percent for krypton-85. The tracer technique has had limited application to date and should be used with care until additional data are available to demonstrate its validity. It should also be recognized that even though the quantities of radioactive materials are small, the growing concern over the use and release of any amount of radioactive materials into the environment may restrict the use of this technique as long as other methods are available that do not involve such materials.

Dual Unsteady State Method--

Muller and Rysinger[30] have recently proposed a procedure for evaluating oxygen transfer rates under process conditions. The dual unsteady state analysis employs unsteady state DO measurements at a high oxygen transfer rate to raise the DO concentration to a value well above that used for process conditions followed by a lower oxygen transfer rate where unsteady state DO measurements are again taken. Field oxygen transfer coefficients, K_La, for each condition may be calculated. In addition, field saturation values can be determined for each transfer rate as well as oxygen uptake rate. The method requires a substantial spread in K_La values from the high oxygen transfer rate condition to the low transfer rate condition and constant uptake rates during the test period. Test results using this method have been recently reported.[31,32]

CONCLUSIONS

Aeration testing with respiring activated sludge systems is not easily carried out and is not recommended over clean water aeration testing for verifying aeration performance specifications. However, with careful data collection and evaluation, it is possible to obtain reasonably valid respiring system test results. After review of current testing experience and the inherent errors of each test, the following conclusions are appropriate:

The testing techniques utilized for in situ testing are by nature very site specific. Truly, there is clearly no "best method" based on current technology.

Batch endogenous testing procedures are more accurate than continuous testing techniques for estimating field transfer rates of various aeration equipment.

The main limitation of continuous testing is the inability to accurately measure the biological oxygen uptake rate.

For many applications, specifically for surface aeration installations, the DO concentration may vary spatially within the tank at a given time during testing under continuous loading conditions; therefore, conventional testing approaches may not be valid for these applications. Further study is required for such installations.

For surface aeration equipment, steady state batch endogenous testing is preferable to unsteady state batch endogenous testing.

For submerged aeration equipment, unsteady state batch endogneous testing is preferable to steady state batch endogenous testing.

Batch endogenous desorption testing using hydrogen peroxide has been demonstrated as an effective technique for measuring field oxygen transfer in surface and submerged aeration systems.

The mass balance approach for determining field oxygen transfer rates requires extensive data collection. For activated sludge systems, the approach appears to have value in small, well-mixed systems, but is simply not as accurate as other tests for most systems. For ASB systems, this approach may be the only practical method available for testing. Therefore, with reasonable care in data collection and analysis, the mass balance approach can be useful for evaluating aeration equipment performance in respiring systems.

The off-gas analysis method for field oxygen transfer measurement has had limited application to date. One current application of this technique is with covered tank, pure oxygen activated sludge systems. However, in view of advancing technology in oxygen concentration measurement equipment and the progressive increase in efficiency of aeration systems generally, this approach deserves further evaluation.

The tracer method for field oxygen transfer determination remains essentially untested. This approach requires and deserves further evaluation.

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SECTION 8

GEOMETRY, SCALE-UP, AND MIXING

INTRODUCTION

The discussion that follows represents a synopsis of the experiences and qualified opinions of the members of the ASCE Subcommittee for Oxygen Transfer Standards. Little published scientific data are available in the literature on this subject. Laboratory and field experiments designed to quantitatively describe scale-up of oxygen transfer and mixing are highly complex, extensive and, therefore, expensive. Currently, there is no basis for a sound generalized theory for scale-up translations. It is the responsibility of the design engineer and the manufacturer to define this translation on a case-by-case basis. The Subcommittee believes that the development of sound testing methods for oxygen transfer in both clean and dirty water systems will ultimately lead to a better understanding of scale-up of these systems.

The clean water reaeration test is intended to model the performance of the installed aerator. This performance is a function of the aerator itself and the installation geometry. Because of the interdependence of the aerator and its environment, scale-up parameters cannot be accurately predicted with laboratory-size aeration equipment. To meet performance specifications, many of the aeration equipment manufacturers have secured large basins for test purposes. In this section, recommendations are made to define the limits between factory and field tests. In general, factory tests can be run with greater precision and more exacting process measurements. The principal weakness of the factory test is the inability to match all installation geometry parameters. Field tests often involve compromises that result in greater data scatter and less precision in measurements.

Because of the lack of substantive published literature, the specific experience of the individuals representing the Subgroup on Geometry, Scale-up, and Mixing formed the basis for this section. The experience of Subgroup members encompasses surface, submerged turbine, coarse bubble, and fine bubble aeration devices. Among the devices not covered are oxidation ditch, deep shaft, and jet types of aerators.

The subsection on Geometric Scale-up defines the differences between field and factory tests that are permitted without process corrections. Differences that exceed specified dimensions require corrections factors. Because these correction factors are specific to each generic aeration device, scale correction factors are not recommended. The test goal is to have a factory test geometry that maintains the aerator parameters related to power, pumping, and tank flow patterns. Specific recommendations on limits of variation for surface, submerged turbine, and diffused air (either rolling or grid pattern) aeration devices are proposed. The range of test variability for the alternative devices (deep shaft, biodiscs, oxidation ditch and jet type aerators) is not addressed.

In the context of this report, mixing is defined as the aerator's ability to disperse DO and to provide a reasonably uniform concentation of solids throughout the basin. These two requirements are of equal improtance, and acceptable performance of one does not necessarily guarantee achieving both. This mixing definition only characterizes the bulk transport phenomena. Micromixing as related to energy dissipation and oxygen transfer in the gas contact zone is not specifically addressed. These factors are an inherent part of all aeration devices, and their impact is indirectly observed by the uptake rate measurement.

DO gradients are intrinsic to the clean water reaeration test. These gradients do not imply problems related to either mixing or mass transfer. DO gradients are most readily observable with surface aerators and the least observable in grid pattern diffused air systems. For a point source aerator (i.e., surface device), oxygen transfer occurs in a small percentage of the total volume. Remote regions of the basin are oxygenated by the bulk transport of oxygen-enriched fluid. Therefore, oxygen gradients observed during reaeration factory tests are dependent on the selection of the sample points, basin turnover, and localized mass transfer rates.

The individual sample point rate of change of oxygen concentration is recommended as the primary indicator of mixing as related to the dispersion of the oxygen-enriched fluid. The local rate of change of oxygen concentration should be relatively constant throughout the basin. There will, however, be a time shift associated with the requirements of bulk transport to the sample point.

In wastewater testing, an essentially uniform suspended solids concentration indicates good mixing. The uniformity or nonuniformity of the DO level is not a good indicator of mixing in an active mixed liquor. The DO level at each point in the basin is dependent on the distance of travel from the point of oxygenation and the uptake rate of the liquor. Because the distribution of DO is strongly dependent on non-mixing process parameters, it cannot be used to indicate the degree of mixing.

DEFINITIONS

Geometry

Geometry is defined as the shape and dimensions of the aeration basin, the location of the aeration devices, and the physical location of ancillary equipment such as draft tubes, baffles, etc.

Mixing

Mixing is the establishment of relative movement within a basin that influences and may be characterized by the degree of uniformity of the concentrations of suspended and dissolved substances.

For aeration applications, mixing is limited to DO dispersion and solids suspension. Defined in this manner, mixing is the ability to

1. disperse DO throughout the basin and
2. provide reasonably uniform solids concentrations throughout the liquid.

It should be noted that reference to either item 1 or 2 provides only a partial description of mixing and does not assure the satisfaction of the other. Both conditions must be met.

Micromixing is not evaluated in this report. Energy intensity and related turbulence are important factors for oxygen transfer in the gas contacting zone. The reaeration test measures the impact of micromixing by quantifying the aerator oxygenation capacity.

Factory Test

The factory test is a clean water reaeration test conducted at a facility dedicated to aerator testing. Instrumentation and laboratory facilities associated with general research requirements are usually included.

Field Test

A field test refers to a test carried out at the site of the aeration equipment installation.

Surface Aerator

A surface aerator is a point source aeration device that contacts the liquid with the ambient gas blanket. Surface aerators are often identified as high- or low-speed aerators.

Submerged Turbine Aerator

A submerged turbine aerator is defined as a point source aeration device that delivers gas to a source of liquid pumping below the liquid surface. Radial and axial impellers are examples of this class of aeration device.

Diffused Aeration

Diffused aeration systems deliver gas below the liquid surface and do not rely on supplemental liquid pumping devices for mixing. Bubble rise creates the turbulence for mass transfer and induces liquid circulation. Subgroups of this category are coarse and fine bubble diffusers.

Diffused aeration systems are characterized by the induced basin flow patterns, which are dependent on the distance between diffusers and diffuser proximity to the basin walls. The rising column of gas bubbles pumps liquid to the surface. The gas disengages at the surface, and the liquid flows outward from the bubble column until it meets a basin wall or flow from an adjacent diffuser.

GEOMETRIC SCALE-UP OF FACTORY TEST TO FIELD CONDITIONS

General Considerations

All tests should be performed in a basin of dimensions close to the application size either in the field or at the factory. In practice, the field test versus the factory test offers a technical trade-off. The factory test is run under carefully controlled conditions prior to field installation, but with possible compromises in water quality differences and system geometry.

The field test in the actual basin often involves compromises in the test procedure. Some common problems associated with field testing are inaccurate or imprecise air measurement, excessive basin size requiring several chemical pumping stations and excessive sample line length, and general inaccessibility of probes, sample pumps, etc. These are only a few of the areas that complicate field test data interpretation and may increase data scatter. In general, field testing of basins in excess of 1-mil gal capacity is not recommended.

Scale-up of factory tests to field conditions requires considerable judgment, since not all geometric variables can be precisely scaled. Experience has demonstrated that a factory test must duplicate full-scale mixing conditions to minimize the need for scale-up factors. The test conditions specified in the following subsections are a best judgment of conditions that eliminate scale-up considerations for various aeration devices. For tests beyond specified limits, aerator performance data must be corrected. Since each generic device may differ in dependence on geometric variables, universal corrections cannot be recommended. The manufacturer and consultant/owner should agree on the correction procedure prior to testing.

Recommended Variation Limits for a Single Surface Aerator

1. Impeller dimensions must be maintained within ±0.5 percent, speed within ±1.0 percent, and submergence within ±10 percent. Changes are limited to hub adjustments for mounting on a factory test shaft.
2. For draft tube devices, tube diameter and proximity must be maintained.
3. Equivalent baffling must be provided.
4. The variation between the ratios of impeller diameter to tank width shall not exceed 6 percent.

5. The variation between the ratios of impeller diameter to water depth shall not exceed 10 percent.

Recommended Variation Limits for a Single Submerged Turbine Aerator

1. Impeller dimensions and speed care to be maintained as indicated above for a surface aerator. Changes are limited to hub adjustments for mounting on a factory test shaft.
2. Proximity of turbine to sparge, draft tube, tank bottom, etc. must be maintained.
3. Design gas rate must be maintained within ±2 percent.
4. Sparge submergence must be maintained within ±4 percent.
5. Equivalent baffling must be provided.
6. The variation between the ratios of impeller diameter to tank width shall not exceed 6 percent.

Multiple Surface or Submerged Turbine Aerators

Observations indicate that each aerator in a large basin operates as though it were in an equivalent cell. It must be recognized that some of the flow from a specific aerator intermixes with that of an adjacent unit, which contributes to the overall mixing pattern of the basin. The assumption that the equivalent cell boundaries bisect the space between adjacent aerators to create defacto basin geometry is a reaonsable one for most mechanical aerator basins and should be evaluated based on the conditions stated above.

Diffused Aeration

Rolling Pattern--

If the distance between adjacent diffusers or between diffuser and basin wall exceeds 50 percent of the submerged depth, a roll-type pattern generally develops. The circulatory motion established under these conditions has a return flow near the basin bottom back to the pumped water column.

Although a roll pattern could be established by a single diffuser, this type of mixing condition is customarily associated with multiple diffusers mounted on a header at a spacing interval appreciably less than 50 percent of submergence. The result is that the major outward flow of the surface is normal to the header. Overall mixing conditions within the basin are then established by the number and placement of these headers along with their proximity to basin walls and bottom. In rectangular basins, the mixing pattern has been traditionally described as either spiral roll or cross roll. A spiral flow mixing condition is established when the header is installed parallel to the long axis of the basin. Conversely, a cross flow mixing condition is established when the header is installed perpendicular to the long axis of the basin.

Recommended Variation Limits for Roll-Pattern Diffused Aeration--

1. The precise diffuser must be used.
2. Diffuser spacing must be maintained within ±5 percent, air flow per diffuser within ±2.0 percent, and water depth within ±1.0 percent.
3. Proximity to adjacent walls, floors, and diffuser lines parallel to the axis of the roll pattern must be held within ±5 percent.
4. Basin width must be maintained within ±5 percent.
5. Basin length parallel to the axis of the roll pattern must be a minimum of 4 ft and must contain a minimum of four diffuser sets.

Grid Pattern--

A grid pattern is any total floor coverage or dispersed diffusers positioning that does not establish a roll. In general, this pattern would result when the maximum spacing between diffuser units in any direction does not exceed 50 percent of submergence.

Recommended Variation Limits for Grid-Pattern Diffused Aeration--

1. The precise diffuser must be used.
2. Diffuser spacing must be maintained within ±5 percent, proximity to the floor within ±5 percent, air flow per diffuser within ±2.0 percent, and water depth within ±1.0 percent.
3. The test basin plan dimensions should exceed the water depth in at least one direction.

4. Each dimension should contain at least four diffuser sets.

MIXING CONSIDERATIONS

General Considerations

Only a partial evaluation of the mixing performance of a specific aeration device can be made based on clean water tests. The clean water test does establish the ability of a device to disperse the oxygen-enriched fluid throughout the basin. Only a mixed liquor test will determine if the aerator performs satisfactorily at maintaining solids in suspension.

Clean Water Test

Test Definition--

Procedures for testing, selecting sample point locations, defining the number of samples, etc. are described in Section 5. Data analysis techniques are presented in Section 4.

DO Gradients--

DO gradients are intrinsic to the reaeration test and do not imply problems related to either mixing or mass transfer. Gradients are readily observed with surface and submerged turbine aerators. The magnitude of these gradients is dependent on sample location, basin turnover, and localized mass transfer. Gradients increase as the pumping rate decreases or the localized oxygen transfer increases. It was shown in Section 4 that large DO gradients imply the existence of localized transfer zones. Modelling of this phenomenon is based on the ideal compartmentalized system, which does not require that DO concentrations be uniform throughout the tank nor that oxygen transfer occur throughout the tank.

Individual Sample Point Analysis--

The rate of change in oxygen concentration with time (mg/ℓ/hr) at the various sample points within the test basin is the primary indicator of mixing as related to oxygen dispersion. The local rate of change of oxygen is the product of the mass transfer coefficient and the driving force associated with the data obtained for a single point. See Section 4 for a complete discussion of completely mixed and compartmentalized system analyses.

The mean and the standard deviation of the local rate of oxygen transfer determined for each point may be used as a basis for estimating the mixing process. The coefficient of variation, CV, is the recommended analysis technique, since it is independent of the magnitude. CV, in percent, is defined by:

$$CV = \frac{s}{\bar{x}} \times 100 \qquad (97)$$

where:

s = standard deviation
$\bar{x}$ = mean

Replicate tests are made using multiple sample points. Using the mass transfer model, a local mass transfer coefficient and saturation value are obtained for each point. These terms are corrected to standard conditions. The product is the uptake at zero DO. The standard deviation and mean values are calculated using no less than two-thirds of the individual uptake values (see Appendix F). For a factory test, the coefficient of variation should be no more than 10 percent. A similar test run in the field cannot be executed with nearly the same degree of precision; a field coefficient of variation could be as high as 15 to 20 percent.

The discarded uptake measurements should be reviewed. If one sample point exhibits consistently low values for all replicate runs, either a poor selection of representative sample points or a mixing problem in dispersing the oxygen-enriched fluid may be indicated. Sample placement problems could be related to

1. baffle proximity,
2. proximity to walls or basin floor, and
3. placement in a mixed flow (gas and liquid) zone in the immediate proximity of the aerator.

Inert tracers (dissolved in the liquid phase) do not quantify mixing conditions related to either oxygen transfer or the suspension of biological solids.

Velocity measurements taken during clean water tests are an indicator of but do not guarantee solids suspension. For some aeration devices, bottom velocities can be less in mixed liquor than in clean water. The relative magnitude of this decrease has not been documented.

In general, horsepower per unit volume is not a direct indicator of mixing or solids suspension capability. The significance of relative power has meaning only when compared to similar aeration devices under similar conditions. The established hydrodynamics are both aeration device and geometry specific.

Mixed Liquor Test

A suspended solids profile taken throughout an aeration basin is the primary quantitative measurement of adequate mixing as related to suspended solids. The absence or presence of bottom solids must be evaluated as either satisfactory or unsatisfactory depending on process design. The coefficient of variation is a relative term whose acceptable limit can best be established by process conditions. For example, low suspended solids concentrations may vary substantially on a percentage basis because of analytical error while high suspended solids concentrations are subject to variability simply because of the combined effects of concentration, flow rate, and location of the return sludge flow. This latter condition can be addressed by shutting off the return sludge flow for some reasonable time (say 15 percent of the detention time) prior to withdrawing samples for a suspended solids profile. The actual limits of CV for a standard will need to be established. Today both 10 and 20 percent are specified. It would appear that 20 percent may be reasonable and still provide evidence of good mixing, particularly if no biological solids are deposited on the bottom.

Procedures for conducting a satisfactory suspended solids profile are reasonably simple and can be adapted to a particular field situation. Samples can be either grab or pumped from remote locations. It should be recognized that baffles, support columns, return flow piping, and stilling baffles create localized conditions that are not representative.

While an essentially uniform suspended solids concentration in an aeration basin indicates good mixing, the uniformity or nonuniformity of the DO concentration cannot always be used for assessing the quality of the mixing.

The DO level at each point in the basin will depend on the balance between DO supply and consumption. The DO consumption distribution will depend on process and basin designs. In a well-mixed reactor, DO consumption will be nearly uniform throughout the basin. Conversely, in a reactor designed to approach a plug flow condition, DO consumption will be relatively high at the inlet where the feed and return sludge are introduced and then decrease along the reactor length.

The DO supply distribution is strongly dependent on aeration system characteristics. In the case where air supply is distributed uniformly about the basin (uniform DO supply), the localized DO level will depend on the localized rate of consumption. However, quite a different situation exists in the case of the DO supply being essentially a point source with bulk transport serving as the principal source of oxygen to remote locations in the basin.

DO gradients exist by definition along the liquid flow path with surface aerators. Gradients also exist but to a lesser extent with submerged turbines. With turbines, DO is introduced at a point and mass transfer occurs throughout the bubble rise path.

From the above discussion, it is concluded that the DO concentration distribution, depending on system design and aeration system characteristics, is in general not a good indicator of the degree of mixing of reactor contents.

RECOMMENDED FUTURE RESEARCH

1. Evaluate the ratiotracer method for potential confirmation of both mixing and oxygen transfer. It would be necessary to demonstrate that the results for mixed liquor are comparable to established procedures.
2. Determine if turbulence significantly affects mixing conditions for aeration. If it does, then the measurement(s) needed must be identified.
3. Conduct measurements of velocity distributions in relation to solids suspension and oxygen dispersion. Compare velocity distributions in wastewater and clean water.

4. Evaluate the feasibility of clean water steady state testing by continuous addition of sodium sulfite. This test would produce steady state gradients, which may simulate or be equated to a system with biological uptake of oxygen.

SECTION 9

GAS FLOW MEASUREMENT

Gas flow measurement is a fundamental part of oxygen transfer testing. The objective of this section is to acquaint the reader briefly with the various types of primary and secondary flow elements available, the required measurements involved, and the standard conditions at which the gas flow data are reported. Furthermore, a complete discussion of the concentric orifice plate is included from the initial design stage through installation and testing. Most of the basic principles discussed herein apply to many of the various flow measurement devices. One subsection deals solely with pulsation caused by positive displacement blowers because of its serious effect on air flow measurements. Also discussed are various calculations based on standard air flow rates (scfm). Finally, recommendations as to appropriate air flow standards for clean water tests are made in the subsection entitled Recommended Standardization.

One reference used in the writing of this section deserves special mention. L.K. Spink's Principles and Practices of Flow Meter Engineering[1] was used extensively in the subsections dealing with the general discussion of primary and secondary flow elements.

PRIMARY FLOW ELEMENTS

A wide variety of flow measurement devices are available. Most of these are capable of providing very accurate results when applied in a proper manner. It is not the intention of this subsection to recommend standard flow measuring devices; rather, the different types of equipment available are discussed. Specifying standard flow measuring equipment would place an unnecessary restriction on the conduct of clean water oxygen transfer tests in the field since actual installations would not necessarily have standard equipment available. This is not true for performance tests on blowers where codes can and are written specifying certain standard flow measuring devices. These codes can be written because blowers are almost always tested in a shop where standard equipment is available.

Flow measuring equipment for clean water testing should not be specified; however, the overall accuracy of the system (primary and secondary flow elements) should be guaranteed to within ±2 percent. If this accuracy cannot be guaranteed, the estimated amount of the inaccuracy should always be stated along with the flow measurements reported.

Head Meters

Most flow meters can be classified as head meters, although some meters are available that operate on entirely different principles. Head meters convert rate of flow into a differential pressure, a mechanical force, or a change of head or level (over a weir or flume). This category of meters includes the orifice plate, Venturi tube, flow nozzle, Lo-Loss flow tube, Dall flow tube, pitot tube (and its variations), pipe elbow tap, target meter, weir, flume, and others.

Head meters have a number of advantages.[1] First, they are usually simple and easily reproducible. Second, flow can be determined accurately without the need for an actual fluid flow calibration of the primary measuring device. Flow rates can be determined by merely knowing the dimensions of the primary device and the properties of the flowing fluid. Furthermore, only well established and easily maintained tolerances are critical in head meters. For the special case of orifice plates, only the pipe and orifice diameters are critical. Other parameters such as concentricity of the orifice in the pipe, location of the differential pressure taps, and degree of smoothness of the pipe itself are not too critical. Any corrosive damage to the orifice bore can be easily seen by removing the plate from the line. A further advantage of head meters is that the differential pressures they produce are very accurately reproducible under the same set of conditions.

Head meters operate on the principle that the rate of flow of fluid is proportional to the square root of the pressure differential. For a given mass flow rate, the reading of the head meter varies inversely as the square root of the density. Head meters are also affected by viscosity, relative pipe size, and velocity. The Reynolds number, however, serves to correlate these parameters with the proper meter coefficients.

Orifice Plates--

The orifice plate is probably the most common type of head meter. It is essentially a thin plate through which a sharp, square-edged orifice has been bored. The ratio of the orifice diameter to the inside pipe diameter is known as the "diameter", orifice", or "beta" ratio. An orifice has a number of variations. Generally speaking, an orifice is either concentric, eccentric, segmental, or annular. The concentric orifice is by far the most widely used. The other variations were derived to handle flows containing solids in suspension and water vapor. Advantages of orifice plates include accuracy, simplicity, cost effectiveness, versatility, and ruggedness. A disadvantage is that they sometimes involve a relatively high permanent pressure loss.

Venturi Tubes--

Venturi tubes are used to measure flows when a relatively low permanent pressure loss is required. Usually they will handle about 60 percent more flow than an orifice plate, but their permanent pressure loss is only 10 to 20 percent of the differential pressure.[2] Venturi tubes are also good for measuring flows with solids in suspension. In addition, for the measurement of a given air flow, they can require less upstream straight pipe than an orifice plate. Venturi tubes consist of a converging and diverging nozzle. The diverging section tends to make the pressure recovery efficient so that the permanent pressure loss is low. The Venturi works on the basic principle that the change in static pressure between two regions of different cross-sectional area is proportional to flow. Static pressure readings are taken in an upstream region of the Venturi and at the throat. Generally speaking, Venturi meters are relatively expensive and somewhat large but, in many situations, these factors are more than offset by their advantages.

Flow Nozzles--

Flow nozzles are similar to Venturi tubes except they consist of a converging nozzle only. While the pressure recovery is not as efficient as with the Venturi tubes, it is still much better than with orifice plates. They will handle about 60 percent more flow than an orifice plate with a permanent pressure loss that varies from 30 to 80 percent of the differential pressure, depending on the diameter ratio.[2] The principle of operation is similar to that of Venturi tubes. Static pressure readings are taken in an upstream region of the flow nozzle and at the trhoat. Generally speaking, flow nozzles are less expensive than Venturi tubes, but are considerably more expensive than orifice plates.

Lo-Loss Flow Tubes--

These devices are similar to flow nozzles except they have an added diverging section that improves the meter's pressure recovery characteristics. Lo-Loss tubes are not quite as efficient as Venturi meters from a pressure recovery standpoint; however, they are somewhat shorter, which reduces the capital cost. They are more pressure efficient than flow nozzles, however, and are slighly more expensive as a result. A Dall flow tube is another type of meter that is similar in principle to the Lo-Loss flow tube.

Pitot Tubes--

The pitot tube or one of its variations, the pitot-static tube or the Annubar (a commercially available device), provides a very low permanent pressure loss. Essentially, pitot tubes are in-line pressure probes that measure velocity head. All variations of the pitot tube measure the stagnation pressure of the flow, which is equal to the static pressure plus the velocity head. The pitot tube requires a separate measurement of static pressure, while the pitot-static tube has a static pressure tap in the side of the stagnation pressure probe. In both cases, the difference between the stagnation pressure and the static pressure is the velocity head.

The pitot tube and the pitot-static tube are limited by the fact that they essentially measure velocity at one point in the flow. Normally, this velocity can be related to the average pipe velocity if the flow conditions are steady; however, upstream pipe disturbances can alter this relationship significantly. The Annubar, on the other hand, measures an average stagnation pressure across the pipe diameter and does a better job of estimating the average pipe velocity. Furthermore, the Annubar differs from the pitot-static tube in that it measures a differential pressure that is somewhat greater than the velocity head due to a slight suction condition created at the low pressure tap. A disadvantage of the pitot tube, pitot-static tube, and the Annubar is that they may sometimes require a pipe size reduction to increase the velocity head since velocity heads in normal air flow applications are usually low.

Other Types of Meters

A number of other types of meters are available for flow measurement. Among these are magnetic meters, turbine meters, variable area meters (rotameters), mass flow meters, rotary lobe gas meters, and others. These meters are good for specific applications and, with the exception of the rotameter, are generally more complex and costly than head meters. For gas flow measurement, however, it would seem that only rotameters and rotary lobe gas meters have wide application.

Rotameters--

The rotameter is actually a variable orifice head meter. It consists of a float in a vertical transparent tube. The inside diameter of the tube is linearly tapered from top to bottom, with the widest portion at the top. Flow enters the tube at the bottom, and the float rises until the weight of the float just balances the lift generated by the buoyance of the float and the pressure differential across it. The headloss through the rotameter is essentially constant and usually fairly low. The rotameter scale is nearly linear with flow. The combination of these factors makes it exceptionally desirable for measuring flows that vary over a wide range (i.e., 10 to 1). Furthermore, the rotameter is not affected significantly by upstream piping disturbances; no straight lengths of pipe are generally required. It is especially suitable for pipe sizes up to 3 in.[3]

Rotary Lobe Gas Meters--

The rotary lobe gas meter is a positive displacement device. It is highly recommended for measuring flows from positive displacement blowers and other pulsating equipment because it is not affected by pulsation as are head meters. Volume flow rate is determined by measuring the rpm developed as the air passes through the meter. Rotary lobe gas meters are usually expensive, but, where high accuracy is required, they are exceptionally good.

In summary, there are a large number of accurate gas flow measurement devices. Each has its own advantages and disadvantages, and one may be better suited to a particular application than another. Holman[4] shows a comparison of the operating characteristics of various flow meters. For a more detailed analysis of the various primary flow elements, the reader is referred to Spink[1] and Cusick.[2]

SECONDARY FLOW ELEMENTS

Secondary flow elements are used to measure the output of primary flow elements. As with primary flow elements, no attempt will be made in this section to specify certain standard secondary flow elements for oxygen transfer studies. Many different types will provide acceptable results if used properly. The only limitation is that the overall flow measurement system accuracy encompassing both primary and secondary flow elements should be within ±2 percent.

The output from head-type primary flow elements is usually a differential pressure. While there are a wide variety of differential pressure measuring devices, they can be generally classified into two basic groups according to whether or not the fluid that exerts the differential pressure is in direct contact with an indicating fluid.[1]

Wet Meters

According to Spink,[1] wet meters are devices where the fluid that exerts the differential pressure is in direct contact with the indicating fluid. This group of meters can be further divided into liquid and liquid seal varieties.

Liquid Meters--

With liquid meters, a difference in liquid level is developed between the high and low pressure sides of the device. Liquid meters are the oldest, simplest, and, generally speaking, the most accurate and reliable of all differential pressure measuring devices. They are excellent in applications where only visual indication is needed and where the static pressures and the nature of the fluid are conducive to transparent tubes. Various types of liquid manometers are available, including the U tube, well type, and mercury float type. Of these, the U tube manometer is the simplest, the differential pressure being the distance between the water columns in each leg. Well manometers are similar to U tube manometers except that the high pressure leg of the device is actually a large reservoir. Since the volume of the reservoir is very large relative to the volume of the manometer indicator tube, it is necessary to read only one leg of the manometer; the fluid level in the reservoir does not change appreciably. An important variation of the well-type manometer is the inclined well-type manometer. Inclining the manometer helps to expand the indicator scale so that the differential pressure can be read more accurately. The mercury float-type liquid manometer is similar to the other liquid meters except for a float attached to an indicating needle following the nercury surface on the high pressure side. This type of meter is very accurate, although relatively expensive, and for many years it was the accepted standard meter for orifice flow measurements.

Liquid Seal Meters--

With liquid seal meters, the differential pressure is determined by the displacement of a piston-like device across which the differential is applied and which acts against the tension of a spring. The meter fluid acts like a seal between the high and low pressure sides of the device. An indicating needle senses the position of the piston. Liquid seal meters are well suited to the measurement of low differential pressures. Generally speaking, they are used where simple, self-powered mechanisms with considerable output power are required. Varieties of this type of meter include the cylindrical inverted bell meter, the Ledoux inverted bell meter, and the ring balance meter (similar in principle to the bell-type meters).

Dry Meters

According to Spink,[1] dry meters are devices where the fluid that exerts the differential pressure is not in contact with an indicating fluid. Dry meters are becoming increasingly popular wherever indication, recording, integration, and/or transmission are required. They are relatively inexpensive compared to the mercury float-type meter. Dry meters are of two basic types: motion and force balance.

Motion-Type Meters--

The motion-type dry meter consists of a bellows system across which the differential pressure is applied; the resulting force deflects a spring, and the motion provides the output. This type of meter is well suited to direct indication, recording, and integration.

Force Balance-Type Meters--

The force balance-type meter employs a diaphragm against which the differential pressure is applied. An electric current or pneumatic pressure develops a second force, and the two forces are made to oppose each other. A sensitive motion detector detects any imbalance in the forces and corrects the second force until they are balanced. The magnitude of the current or pressure of the second force is then directly proportional to differential pressure. This type of meter is used primarily as a pressure transmitter to a remote location.

Selection of a Secondary Flow Element

As with primary devices, the selection of a specific secondary device for a given application depends on a number of factors. Generally speaking, where visual indication is sufficient, liquid manometers are suitable as they are simple, low cost, rugged, and accurate. Other needs may dictate a requirement for other types. For a much more detailed discussion of various secondary devices and their specific application, the reader is referred to Spink.[1]

Certain basic guidelines should be followed in selecting secondary flow elements. First of all, a secondary meter should always be sized to measure the actual differential pressure, not the high and low pressures separately followed by an arithmetic subtraction. The latter method usually results in a substantial loss of accuracy.

Furthermore, it may often be appropriate to have several secondary elements with different differential pressure ranges available for use with a given primary element, since it is often the readability of the secondary element that limits the flow range of the overall gas flow measurement system.

Finally, it is usually appropriate with manometers to use either water or mercury for the manometer fluid when making field differential pressure measurements. Fluids that have a specific gravity close but not equal to that of water should be avoided, since the possibility of contamination with water always exists in the field. Mercury, on the other hand, has a specific gravity that is so much different from that of water that minor contamination with water does not affect the readings significantly.

CONNECTIONS BETWEEN PRIMARY AND SECONDARY FLOW ELEMENTS

A number of factors should be considered when making differental pressure connections between primary and secondary flow elements:

1. The manometer should be located in a shaded area as close to the primary element as possible.
2. For gas flow, the manometer should be mounted above the air line so that the tubing slopes at least 1 in./ft. This allows any condensation in the tubing to roll back into the air lines.
3. For distances less than 50 ft, the tubing between the primary and secondary elements should be at least 3/16 in. inside diameter. For distances greater than 50 ft, the diameter should be increased by approximately 1/8 in. for each additional 50 ft.
4. For greatest accuracy, the tubing on both sides of the head meter should be of the same length and should be in the same thermal environment.

The tubing used to connect the primary and secondary flow elements may be made of a number of commercially available materials. Copper tubing or pipe is recommended for permanent installations. Materials such as rubber, polyethylene, and vinyl are fine for less permanent installations and are more amenable to changes in the way the system is connected. Special care should be exercised when using hard-walled tubing such as polyethylene in an outside environment since low temperatures may cause the tubing to crack.

Valves should be placed on both primary and secondary elements. Needle valves and other restrictive valves such as plug and globe values are not recommended. Equalizer arrangements and check valves should be used on manometers where a possibility of excessive differential pressure exists. The equalizer is merely a cross-connection between the high and low pressure sides of the manometer with a manual shut-off valve. Lever-operated, one-quarter turn gas valves are very convenient for this application. Generally speaking, the equalizer valve is left open unless a reading is taken. This protects the fluid in the manometer against over-pressure. Some manometers, such as those used for measuring line pressure, may not require either equalizers or check valves since the possibility of over-pressure may not exist.

A number of tubing connectors are available. For permanent installations, double-ferruled connectors are recommended. These can be used on any hard-walled tubing and can also be used on soft-walled tubing with the proper tubing insert. Fittings can be bought that will adapt to various types and diameters of tubing and pipe. For less permanent installations, barbed tube or hose connectors are recommended for use with flexible tubing such as rubber or vinyl. This type of fitting, which makes connecting and disconnecting tubing quick and easy and yet assures a positive seal, is limited to low pressure installations.

TROUBLESHOOTING THE FLOW MEASUREMENT SYSTEM

After a gas flow measurement system is designed and built, it is essential that it be checked out in detail before it can be used with confidence. First, care should be taken to ensure that the system has been built according to specifications. This step should be followed by a thorough leak test. The primary element, secondary element, pressure taps, tubing connections, valves, and other related items should all be checked with a soap solution when the line is under relatively high pressure. In the case of differential pressure flow systems, after the leak test has been performed, the response of the manometers should be checked. A manometer should respond rapidly to the pressure differential it measures. If it does not, this is a sign of a possible leak. An additional leak check should be performed by closing the valves on the primary element when differential pressure is being measured. If the manometer reading changes significantly or drifts gradually, there may be a leak in the tubing or fittings between the manometer and the primary element valves. An increasing differential pressure may indicate a leak to atmosphere in the low pressure tubing; a decreasing differential pressure may indicate a leak to atmosphere in the high pressure tubing. A decreasing differential pressure may also indicate a leak in the equalizer valve between the high and low pressure sides of the manometer.

It is also important to make sure that the differential pressure manometers zero properly. This procedure should always be performed with the system under pressure. It is also important to make sure that the blower "sees" the primary element during this check; in other words, no valves should be closed between the blower and the primary element. This precaution is necessary since, if pulsation is a problem, the manometer zero may be significantly affected (see the following Pulsation subsection).

The manometer readings obtained at different flow rates and line pressures should be observed and the reasonableness of the readings ascertained. Significant oscillations can have an adverse effect on air flow measurement. These oscillations are caused either by unsteady conditions in the line resulting from inadequate lengths of straight pipe, aeration tank water level variations, or, possibly, to blower pulsation, although it is not to be inferred from this that blower pulsation is always accompanied by manometer fluid oscillations. If an oscillation problem exists and if it is related to inadequate lengths of straight pipe, then straightening vanes[1,2] or a new orifice plate location may help. If it is related to aeration tank water level variations, this situation can be at least partially overcome by introducing a headloss in the aeration tank. If the oscillation problem is related to pulsation, it can usually be overcome by one of the methods listed in the following Pulsation subsection.

An additional check should be made to determine if pulsation exists in the system. The manometer differentials should be read with two different lengths of connecting tubing, ranging from several to 15 ft or more in length. If the differential reading varies with tubing length, this can be a sign of pulsation.

It is an excellent idea to check the flow measurement system against as many known flow rates as possible. It should be kept in mind that agreement at just one flow rate does not guarantee agreement at other flow rates and line pressures. Positive displacement blowers can provide a very good check on an air measurement system as long as an accurate blower air flow computation is performed (the information necessary to perform this computation is usually available from the manufacturer). Indirect inferences as to flow rate can also be used to check the flow measurement. These include oxygen transfer measurements and diffuser headlosses.

In summary, after a differential pressure flow measurement system has been constructed, the following checks should be performed as a minimum requirement:

1. Make sure that the system has been built according to specifications.
2. Perform a thorough leak test.
3. Check the response of the manometers to changes in differential pressure.
4. Check the manometer zero under pressure.
5. Observe the manometer readings produced at different flow rates and line pressures.
6. Check the differential pressure readings with several different lengths of connecting tubing.
7. Check the flow measurement system against as many known flow rates as possible.

PULSATION

Pulsation, as used here, refers to the high frequency pressure oscillations that are produced by positive displacement blowers, reciprocating compressors, and other devices that create dynamic disturbances. It is a well-known fact that pulsation can be a major source of error with head meters. The pressure oscillations at the two pressure taps of the head meter do not necessarily cancel out, with the result that the differential pressure produced may be considerably different than that which would have been produced under steady flow conditions. Different types of head meters are affected differently by pulsation, but it is probably fair to say that all are affected to some extent. This subsection deals with the symptoms of the problem as well as methods of correcting it.

Based on personal experience of Subcommittee members with pulsation problems, it can be stated that pulsation may be accompanied by one or more of the following symptoms:

1. The manometer will not zero under a no-flow condition with the

blower operating the line.

2. The manometer readings are affected by the length of the connecting tubing.

3. The manometer readings may show significant fluid oscillations.

It is important to point out that the absence of the these symptoms does not necessarily mean that the pulsation problem does not exist. If one or more symptoms are discovered, however, pulsation may be present.

As far as corrective measures are concerned, Spink[1] has the following to say:

> "The practical approach is to reduce or eliminate the pulsation by installing added capacity or volume together with added pressure drop in the line between the meter and the source of pulsation."

He also goes on to say:

> "Measurement may be improved by one or a combination of .....
>
> 1. operating at a higher differential, i.e., in a multiple meter run installation, shutting off one or more runs,
> 2. installing a higher range differential guage and changing operating conditions in order to use the increased range with the existing orifice, as by reducing the flowing pressure, etc.,
> 3. reducing the pipe run diameter so as to use a higher orifice-to-pipe diameter ratio, still operating at differentials as high as practicable (increasing the d_0/d ratio will reduce the pulsation error if the operating differential remains constant),
> 4. installing mufflers, headers, restrictions, or combinations of capacity and pressure drop between the primary device and the source of pulsation to reduce pulsation amplitude, and
> 5. locating the primary device at a point where the pulsation amplitude is lower (as on the suction side of compressors)."

A common approach to solving a pulsation problem is the installation of a reservoir or receiver (added capacity) between the blower and primary device. For reciprocating units, according to Ingersoll Rand's Compressed Air and Gas Data,[5] "the combination of receiver volume and throttling will usually dampen the pulsations sufficiently if the receiver has a minimum volume of 40 times the displacement of one stroke of the adjacent cylinder of a reciprocating unit."

Specific information on the design of an air flow system so that pulsation can be avoided is contained in the AGA Gas Measurement Manual.[6] In any system design where positive displacement compressors are being considered, primary emphasis should be on providing substantial volume and headloss between the compressor and the primary device. Once built, each system should be checked for the symptoms mentioned earlier.

REQUIRED MEASUREMENTS FOR GAS FLOW DETERMINATIONS

A number of measurements are required for accurate gas flow determinations. As a minimum, these measurements include

1. differential pressure (if applicable), h
2. flow rate (if applicable), Q
3. flowing gas temperature, T_f
4. flowing gas pressure (static pressure), p_f
5. ambient temperature, T_a
6. ambient pressure, p_a, and
7. ambient relative humidity, RH_a.

Other readings may be necessary for specific types of flow meters.

The differential and static pressure readings should be made with a manometer of some type. Unless flow totalization or recording is required, a simple U-tube or well-type manometer works very well. Pressure gauges can be used for static pressure determinations, but experience has shown that, unless these gauges are of the oil-filled variety or are at least protected with a pulsation damper (snubber), they can be rendered useless in a short period of time by vibration and pressure oscillations. A mercury-filled manometer is more rugged and accurate.

Flowing gas temperature can be read with a bimetallic dial thermometer that is mounted permanently in the pipe. These thermometers can be bought with probes of varying lengths for different pipe sizes. Where electronic determinations are required, as in temperature compensation circuits, thermistors can be employed. In any case, the probe should extend well into the center of the pipe.

Ambient temperature can be determined with any number of commercially available wall-mounted thermometers. Care should be taken to obtain these readings in the shade as direct sunlight will cause erroneously high readings due to the radiant energy of the sun.

Ambient pressure should be determined with a good quality mercurial barometer. These readings should also be taken in a shaded area, and corrections should be made for the thermal expansion of the brass indicating scale, the change in mercury density with temperature, and the effect of the earth's gravitational field. Tables for making these corrections are usually included with the barometer.

Relative humidity readings should be taken with a hygrometer or a psychrometer. The sling psychrometer, in particular, is portable and inexpensive. Usually, wet and dry bulb thermometer readings are taken and are converted to relative humidity with the use of tables that accompany the device. Some hygrometers are available that read relative humidity directly.

STANDARD CONDITIONS

Since gases are compressible fluids, and in some instances may contain varying amounts of water vapor, the ratio of mass flow to volumetric flow is not a constant, but depends on the temperature, pressure, and water vapor partial pressure. The need to relate mass flow to a volumetric flow by a constant resulted in the term standard cubic feet per minute (scfm). This term refers to an imaginary volumetric flow rate; it is that flow that would exist if the same mass flow of dry gas existed at standard conditions of temperature, pressure, and relative humidity. This volumetric flow rate can be multiplied by a constant factor to obtain the mass flow of dry gas or by a different constant factor to obtain the mass flow of gas at standard humidity.

Standard conditions for air flow measurement are usually taken as 68°F

(20°C, 528°R), 14.70 psia (1 atm., 760 mm Hg), and 36 percent relative humidity. Standard temperature is sometimes taken as 60°F, particularly by the natural gas industry. Blower manufacturers and others, on the other hand, sometimes use 70°F. It is felt that 68°F is the most commonly used temperature standard in the oxygen transfer field, and this temperature has been selected for use here. It should also be pointed out that for gases other than air, the relative humidity standard is zero rather than 36 percent.

CONVERSION OF STANDARD VOLUMETRIC FLOW RATES OF AIR TO MASS FLOW RATES OF OXYGEN

One method of converting a volumetric air flow rate in scfm to a mass oxygen flow rate in lb/hr is to first calculate the fraction of the scfm flow that is dry air. This step can be accomplished by multiplying by the mole fraction of dry air at standard conditions. Mole fraction is related to partial pressure in the following manner:

$$Y_{das} = (14.70 - p_{ws})/14.70 \qquad (98)$$

where:

Y_{das} = mole fraction of dry air at standard conditions at 68°F, 14.70 psia, and 36 percent relative humdity

p_{ws} = partial pressure of water vapor at standard conditions at 68°F, 14.70 psia, and 36 percent relative humdity = 0.122 psia, f/L^2

Making this substitution, $Y_{das} = 0.9917$. Thus, the flow rate of dry air at standard conditions becomes:

$$Q_{das} = 0.9917\ Q_a \qquad (99)$$

where:

Q_{das} = dry air porition of Q_a(cfm), L^3/t

Q_a = air flow at standard conditions of 68°F, 14.70 psia, and 36 percent relative humidity (scfm), L^3/t

The density of dry air at standard temperature and pressure is 0.0752 lb/ft^3. Thus, the weight flow of dry air in lb/hr is given by:

$$w_{da} = (0.0752)(60)Q_{das} = 4.513\ Q_{das} \qquad (100)$$

where:

w_{da} = weight flow of dry air (lb/hr), m/t

Combining Equations 99 and 100 yields:

$$w_{da} = 4.475\ Q_a \tag{101}$$

Dry air is variously taken as 23.0 to 23.2 percent by weight.[7] Using 23.1 percent as an average, the weight flow of oxygen is related to the standard volumetric flow of air in the following manner:

$$w_{o_2} = (4.475)(0.231)Q_a = 1.034\ Q_a \tag{102}$$

where:

w_{o_2} = weight flow of oxygen (lb/hr), m/t

CONVERSION OF VOLUMETRIC FLOW RATES FROM STANDARD TO ACTUAL CONDITIONS

It is often necessary to determine the actual cfm flow of air, particularly when correlations are being made with headloss. From ideal gas considerations, the scfm and cfm air flows are related by temperature, pressure, and relative humidity in the following manner:

$$Q = (14.70/p_f)(T_f/528)[(p_b - p_{bw})/p_b][p_f/(p_f - p_w)] \tag{103}$$

where:

Q = gas flow (cfm), L^3/t

For air, using standard conditions of 68°F, 14.70 psia, and 36 percent relative humidity, the expression reduces to:

$$Q = 0.0276\ T_f Q_a/(p_f - p_w) \tag{104}$$

RECOMMENDED STANDARDIZATION

Recommended standards for air flow measurements taken during a clean water test are summarized in Table 24. In summary, all data should be reported in terms of the standard conditions of temperature, pressure, and relative humidity shown. The guaranteed accuracy of the overall flow measurement system (primary + secondary flow elements) should be within ±2 percent. If this cannot be guaranteed, then, it should be so stated along with any of the flow measurements reported. Furthermore, during the conduct of any clean water test, the air flow rate should not vary by more than ±3 percent of the average value. If the air rate fluctuation is greater than this, the oxygen

TABLE 24. RECOMMENDED STANDARDS FOR GAS FLOW MEASUREMENT DURING CLEAN WATER OXYGEN TRANSFER TESTS

Item	Recommended Standard
Standard conditions for air flow measurement	68°C, 14.70 psia, 36 percent relative humidity
Standard conditions for gas flow measurement (other than air)	68°C, 14.70 psia, 0 percent relative humidity
Overall flow measurement system accuracy	±2%
Maximum allowable variation in air flow rate during the conduct of the clean water test	±3%
Relationship between mass flow rate of oxygen and standard volumetric flow rate of air	$w_{o_2} = 1.034\ Q_a$
Standard primary element	None specified
Standard secondary element	None specified
Meter design, construction, installation, and operation	In accordance with accepted practice
Receiver tank for positive displacement blowers	Strongly recommended

transfer test should be considered unacceptable. Also, the weight flow of oxygen in lb/hr should be related to the standard volume flow of air in scfm by a factor of 1.034.

As mentioned previously, no standardization of air flow measuring equipment should be required; however, design, construction, installation, and operation should be in accordance with accepted practice. Finally, a receiver or pulsation tank is strongly recommended in any air flow systems where a positive displacement blower is used.

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SECTION 10

POWER MEASUREMENT

Accurate determinations of both gas and turbine horsepower are essential in the field of oxygen transfer. Basically, they are needed for aeration system design, economic comparisons, and data correlations. This section discusses the meaning of various power terms used in the oxygen transfer field and attempts to point out where confusion exists. It also discusses various methods commonly used to make power determinations, as well as the limitations of certain approaches. Particular emphasis is given to the need to standardize the way in which clean water power data are reported for advertising or comparison purposes.

GENERAL DEFINITION OF TERMS

Some of the basic power terms used in oxygen transfer testing are defined in general terms below. These definitions are more fully elaborated on later in this section.

1. Gas power - as used here, that part of the total aeration system power that is specifically related to the gas supply.
2. Turbine pump power - that part of the total aeration system power that is specifically related to the operation of a mechanical device, such as a turbine or pump.
3. Water power - the work performed on the water in the form of either gas or turbine energy.
4. Total water power - the sum of both the gas and turbine water power.
5. Delivered power - in the case of gas power, the theoretical power required at the blower to deliver a given mass flow of gas through a diffuser system operating under a given static head; in the case of turbine power, the power required at the output shaft of the

gear box to turn a shaft and impeller at a given rpm in water, under actual conditions.

6. Total delivered power - the sum of both the gas and turbine delivered power.
7. Brake (shaft) power - the power developed or required at the shaft of a rotating piece of equipment.
8. Total brake power - the sum of both the gas and turbine brake power.
9. Wire power - the electrical power drawn by a motor.
10. Total wire power - the sum of both the gas and turbine wire power.

THE NEED FOR STANDARDIZATION

When reviewing clean water test data, it is often unclear as to how reported power determinations were actually made. Confusion may exist as to the following:

1. Were the power determinations reported as delivered, brake, or wire horsepower?
2. Were the power determinations measured directly or calculated?
3. If calculated, what calculation procedure was used (adiabatic, polytropic, etc.)?
4. Were actual, standard, or some other ambient conditions used?
5. Was the effect of line loss as well as diffuser loss included?
6. Did the determinations include a power suction loss?
7. At what gas temperature was the diffuser headloss measured?
8. At what water temperature was the turbine power draw determined?
9. What blower, motor, and drive efficiencies were used?

Questions such as the above should not exist about any reported data. In certain cases, rather than just answering questions like the above in the context of a report, it would be desirable to report standard power data. In other words, standard conditions and procedures should be established for power measurements such that when reference is made to standard delivered, brake, or wire horsepower, no confusion exists as to what is meant. This standardization would apply primarily to cases where the results of shop or field tests are to be reported for advertising or comparison purposes.

In the case of shop and field performance tests, where power determinations are to be made for equipment acceptance under specified design conditions, the reporting of standard power data alone would certainly not be appropriate. Power results should be reported in terms of specified design conditions; however, the additional reporting of standard power data would facilitate the comaprison of various shop and field performance tests made around the country.

It would appear to be appropriate, therefore, to define a set of standard conditions and procedures for power determinations. It is not the purpose of this section to determine the standard conditions and procedures to be used but, rather, to demonstrate a need for standardization where it exists. Any standard conditions or procedures should be established by selected representatives from the oxygen transfer field. Possible standards will be suggested, however, where appropriate.

In the case where reporting standard power data is appropriate, arguments can be made for reporting only standard delivered power instead of standard delivered, brake, and wire power. For one thing, it would not be necessary to define standard motor, blower, gear box, and coupling efficiencies. It is recommended, however, that standard brake and wire horsepower also be reported. Comparisons made between component aeration systems would then be more realistic. Due to the different efficiencies associated with a blower compared to a turbine, reporting only standard delivered power would be very misleading as far as the overall power requirements of the two aeration systems are concerned.

Standard clean water power numbers should not be used directly when extrapolating clean water test results to aeration system design. When applying clean water test data to design, it is important that power determinations be made that use actual ambient and operating conditions and power formulations that apply directly to the blower being used. The purpose of standard power determinations is only to put the comaprison of various types of aeration systems on an even footing.

GAS POWER

Gas power is that part of the aeration system power requirement that is specifically related to the gas supply. It refers to the general class of gas power determinations, including water, delivered, brake, and wire power. In these cases where shop and field perforamnce tests are run for equipment acceptance and the actual blower-motor combination is used, it is appropriate to make direct power measurements. In those cases where gas power determinations must be made without reference to a specific blower or motor, it is more appropriate to calculate the power. Most often, this calculation is based on the adiabatic compression equation.

Adiabatic Compression Equation

The adiabatic equation can be derived from basic thermodynamic principles. Fair and Geyer[1] have presented the derivation. It should be noted, however, that the final form of the equation in their derivation makes some assumptions as to ambient conditions. Basically, the equation represents the work done along an adiabatic path between two gas states. It is based on the ideal gas equation, $pV = n\bar{R}T$, and the adiabatic relationship, pVc_p/c_v = constant, where c_p and c_v are the specific heats at constant pressure and volume, respectively. The work performed is calculated by integrating the pressure-volume work between the two states:

$$\text{adiabatic work} = \int_{p_1,T_1}^{p_2,T_2} \qquad (105)$$

After integrating and including the efficiencies of the various components, the following general form of the adiabatic equations can be obtained:

$$\text{wire horsepower(adiabatic)} = [w\bar{R}T_1/(550\ Ke_be_de_m)][(p_2/p_1)^K - 1] \qquad (106)$$

where:

w = weight flow of gas (lb/sec), m/t

$\bar{R}$ = universal gas constant, (ft-$lb_f/lb_m\cdot$°R), $Lfm^{-1}T^{-1}$; 53.5 for air

T_1 = absolute inlet temeprature, °R

p_1 = absolute inlet pressure (psia), f/L^2

p_2 = absolute discharge pressure (psia), f/L^2

K = $(k - 1)/k$; 0.283 for air

k = ratio of specific heats of air at constant pressure and constant volume, c_p/c_v; 1.395 for air

e_b = blower efficiency, decimal percent

e_d = drive efficiency, decimal percent

e_m = motor efficiency, decimal percent

The basic form of this equation can be found in Reference 2. The case where the motor efficiency, e_m, is equal to 1 is equivalent to the motor brake power. The case where the motor efficiency, e_m, and the drive efficiency, e_d, are both equal to 1 is equivalent to the blower brake power. Finally, the case where all the efficiencies are equal to 1 refers to the perfect adiabatic case where there are no losses.

Substituting the known quantities for air into Equation 106 yields:

$$\text{wire horsepower(adiabatic)} = [(5.729 \times 10^{-3})\gamma_{air}Q_aT_i/(e_be_de_m)]\,[(p_2/p_1)^{0.283} - 1] \qquad (107)$$

where:

γ_{air} = weight density of air at the temperature, pressure, and relative humidity for which Q is reported (lb/ft^3), m/L^3

Q_a = air flow (cfm), L^3/t

It is important to note the limitations of the adiabatic compression equation. Too often it is used with the idea that it accurately describes the operation of all blowers. While many blowers are nearly adiabatic, some may be more adequately described by a polytropic relationship. The polytropic power equation for air is similar to the adiabatic power equation for air (Equation 107) except that the value of 0.283 is replaced by $0.283/e_{poly}$, where e_{poly} is the polytropic efficiency of the blower (a purely thermodynamic property). Further, the value of e_b is replaced by the mechanical efficiency of the blower.

Both the polytropic and adiabatic equations have been used to describe the operation of centrifugal blowers. The operation of positive displacement blowers, on the other hand, has usually been described with the adiabatic equation. With this in mind, it is probably reasonable to use the adiabatic equation when reporting clean water data, since it has been used to describe the operation of both types of blowers. The determination of the polytropic and mechanical efficiencies of a blower is usually not easy. Comparisons made between various aeration systems on the basis of adiabatic power may not hold true when the comparison is made on the basis of polytropic power. Also, comparisons made between the power requirements of a given aeration system at various water depths may differ when polytropic power is used instead of adiabatic power.

It should also be kept in mind that the adiabatic equation (Equation 106 with all efficiencies = 1) should not generally be used to calculate the relative internal energy level of the gas at a particular point in the gas distribution piping. The relative internal energy level, as used here, refers to the increase in internal energy above that at ambient conditions. From the First Law of Thermodynamics, the increase in internal energy of a gas is the difference between the work performed on it and any heat loss that may occur. For an adiabatic process, where the heat loss is zero, the increase in internal energy of gas is, thus, equal to the work performed on it.

The process of supplying air to an aeration tank, however, is not perfectly adiabatic in nature. The blower is not perfectly efficient, adiabetically speaking, and the pressure and thermal losses in the distribution piping are not usually adiabatic. Thus, the adiabatic equations cannot be used to estimate the relative internal energy level of the gas. The adiabatic equation can be used, however, at any point in the gas distribution piping to determine the adiabatic work that would be required to compress the gas to the line pressure at that point. This is often a very meaningful calculation.

The adiabatic equation (Equation 106 with all efficiencies = 1) cannot be used to calculate the work that is actually performed in the water. The actual water horsepower due to the gas is the pressure-volume work that is done as the gas rises and expands throughout the depth of the aeration tank. This work is probably much closer to being isothermal in nature, since the expansion probably takes place at a temperature close to that of the water due to the very high heat capacity of water relative to the gas. If no oxygen transfer occurred in the tank, it would be theoretically possible to calculate the work performed in the water with the following integrations:

$$\text{isothermal work} = \int_{\text{gas release point}}^{\text{water surface}} p dV \qquad (108)$$

Using the ideal gal law and assuming the temperature is constant:

$$\text{isothermal work} = n\bar{R}T = \int_{\text{gas release point}}^{\text{water surface}} dV/V \qquad (109)$$

$$= n\bar{R}T \ln(p_{inlet}/p_{surface})$$

where

n = number of moles of gas

p_{inlet} = absolute static head at the gas release point, f/L^2

$p_{surface}$ = absolute pressure at the aeration tank water surface, f/L^2

Since, under dynamic conditions, oxygen transfer does take place, performing this integration exactly is not possible. It would seem, however, that Equation 109 could be used to provide an approximation to the maximum gas work performed in the water at a time of zero oxygen transfer. Knowing the actual percent transfer, it is possible to place a lower limit on the actual gas work performed in the water (based on mass considerations). Thus, Equation 109 might be used to describe an approximate range for the actual gas work performed in the water.

Water power is really only significant from a theoretical standpoint. It may be of some value in data correlations particularly in regard to mixing. Generally speaking, however, what is most important is the power required to deliver a given quantity of gas through a diffuser system under specified conditions. As mentioned previously, this can usually be approximated by the adiabatic compression equation.

Gas Delivered Power

Gas delivered power is usually considered to be the theoretical adiabatic power (Equation 106 with all efficiencies = 1) required at the blower to supply gas through a diffuser system operating under a given static head. For the special case of air:

$$\text{air delivered horsepower} = (5.729 \times 10^{-3})\gamma_{air}Q_aT_1[(p_2/p_1)^{0.283} - 1] \tag{110}$$

After conversations with a number of people in the oxygen transfer field, a number of different opinions exist regarding the way this equation should be applied. First of all, many experts consider the delivered horsepower to be the adiabatic power required at the inlet to the diffuser, rather than at the blower. In other words, there is some confusion as to whether line losses should be included in the gas delivered horsepower calculation.

It should be considered at this point that the adiabatic equation (Equation 106) provides a closer approximation to the actual power required when applied at the blower. For this reason, it would appear that the best definition of gas delivered horsepower would be the theoretical adiabatic power required at the blower. In most cases, the horsepower so calculated would be more realistic and practical.

The gas delivered equation (Equation 106 with all efficiencies = 1) can be used with actual ambient and operating conditions to approximate the gas delivered horsepower requirement on a given day at a given installation. This is sometimes necessary from the standpoint of aeration system design and plant operation. When reporting clean water test data for advertising or comparison purposes, however, the use of actual ambient and operating conditions to calculate gas delivered horsepower can be very misleading. It is clear from the gas delivered horsepower equation (Equation 106 with all efficiencies = 1) that it is possible to obtain a wide range of delivered horsepowers for a given mass flow of gas and gauge discharge pressure because the ambient conditions are also important in determining the horsepower requirement. This fact may tend to cloud the real issue when comparisons are made between various clean water tests across the country. What is really important from a gas standpoint is the gas flow and gauge discharge pressure at which a given test was conducted. Different ambient conditions for the same gas flow and gauge discharge pressure can vary the power requirements by over 30 percent. In the case of power data to be used for advertising and comparison purposes, calculation of a standard gas delivered power could be made from the gas flow and discharge pressure by assuming certain standard conditions.

The use of actual system line losses could also very well tend to confuse diffuser horsepower comparisons made across the country. Since line losses for any diffuser system are usually easily controlled by varying pipe size, it would be desirable to assume a standard line loss when calculating the standard gas delivered power. Furthermore, if possible, diffuser headloss readings should be corrected to a standard gas temperature before using them to calculate standard gas delivered power.

There is a need, therefore, to standardize the adiabatic power measurements when reporting clean water test results for advertising or comparison purposes. One proposed definition of standard air delivered horsepower might be that power calculated from the adiabatic compression equation (Equations 110 or 107 with all efficiencies = 1) when compressing an scfm flow rate of air at standard ambient conditions of 68°F, 14.70 psia, and 36 percent relative humidity to a discharge pressure set by the static head, a 1.0-psi line loss, and a diffuser headloss corrected to 68°F. In addition. a 0.1-psi suction loss would be assumed for the blower inlet.

The standard ambient conditions mentioned are, of course, the present standards for air flow measurement. The value of 1.0 psi is considered to be a reasonable average system line loss, but, certainly, many other values could be used. The standard temperature of 68°F was selected for the diffuser headloss correction because it is felt that in most cases the diffuser air temperature is near that of water, and the standard water temperature for oxygen transfer measurements is 68°F. Finally, the blower suction loss of 0.1 psi is felt to be fairly representative.

Making these substitutions into the air delivered power equation (Equation 110), the following expression for standard air delivered power is obtained:

$$\text{standard air delivered horsepower} = 0.227\, Q_a \{[(15.7 + h_L + H)/14.6]^{0.283} - 1\} \tag{111}$$

where:

h_L = diffuser headloss corrected to 68°F (psi), f/L^2
H = static head (psig), f/L^2

While it is realized that this equation is not an actual power determination, and is definitely not to be used for design work, it does make comparisons of clean water test data collected on different days in different parts of the country more meaningful.

At this point, it is appropriate to discuss the three measurements, Q_a, H, and h_L, that are required for the determination of standard air delivered power from Equation 111. The required accuracy of the standard air flow, Q_a, should be within ±2 percent. The static head determination, H, can be made most accurately with the use of a bubbler device. The bubbler is essentially a vertical pipe with an outlet at the diffuser level. In practice, a small air compressor can be used to bubble air down through the bubbler pipe to the diffuser level. The bubbler piping should be large enough so that virtually no friction losses are obtained. A connection is made between a pressure tap in the bubbler piping and one leg of a mercury manometer so that static pressure can be read directly. A bubbler is an accurate way of measuring the static head because it compensates for the gas holdup above the diffusers. The required accuracy on this measurement is ±1 percent.

Diffuser headloss, h_L, can be determined by reading diffuser inlet pressure against the static head with a manometer. In order to sense diffuser inlet pressure, a pressure tap should be installed at the inlet to a diffuser(s). A connection should be made to one side of a manometer with the bubbler static pressure on the other side. The resulting differential will be the diffuser headloss. The required accuracy on this measurement should be ±5 percent. To accompany the headloss reading, measurements should also be taken of the air flow, diffuser air temperature, and static head. As mentioned previously, for standard power determinations, the diffuser headloss should be corrected to a standard diffuser air temperature at 68°F. A summary of recommended gas flow measurement standards applicable to standard gas delivered power was shown previously in Section 9, Table 24.

Gas Brake Power

Brake or shaft power refers to the power associated with the rotating shafts of mechanical equipment. It can refer to either input or output power, depending on the device. With motors, for example, the brake power developed is the motor output power. With blowers, the brake power required is the blower input power. In an actual application where the motor is connected to the blower by means of a flexible coupling, belt drive, or gear reducer, power losses occur between the motor and the blower. The motor brake power developed is greater than the blower brake power required by the amount of loss. It is important, therefore, when talking about gas brake power to distinguish between the motor and blower brake power.

In the case where actual blower-motor combinations are being tested for equipment acceptance, it is appropriate to make direct power measurements with the techniques discussed in the later subsection on Shaft Power Determinations. The required accuracy should be ±2 percent. When estimates of brake power are required without reference to a particular blower-motor combination, they should be calculated from the theoretical adiabatic power by using the appropriate efficiency.

The blower brake power is related to the theoretical adiabatic power by the blower efficiency, e_b:

$$\text{blower brake power} = \text{theoretical adiabatic power}/e_b \qquad (112)$$

where e_b is in decimal percent.

The blower efficiency depends on a number of factors, including blower type (centrifugal or positive displacement), number of stages, and load (including speed, pressure differential, and ambient conditions). A suggested range of blower efficiencies applicable throughout the field today is 0.5 to 0.8. Where power measurements are made directly and theoretical adiabatic power is calculated from the adiabatic equation (Equation 106 with all efficiencies = 1), the power efficiency can be determined from Equation 112.

Motor brake power is related to the blower brake power by the drive or coupling efficiency, e_d:

$$\text{gas motor brake power} = \text{blower brake power}/e_d \qquad (113)$$

where e_d is in decimal percent.

This efficiency varies with the type of coupling or drive and with load. Coupling or drive efficiencies are usually fairly high, probably between 0.9 and 1.0. If brake power measurements are made directly for the blower and motor, then the efficiency, e_d, can be determined from Equation 113.

When reporting clean water test data for advertising or comparison purposes, it is appropriate to use a standard gas brake power. It is recommended that standard gas brake power be related to standard gas delivered power by a standard blower efficiency, e_{bs}, and a standard drive efficiency, e_{ds}. Reasonable values for these standard efficiencies might be 0.70 and 0.95, respectively, although many others could be proposed.

Gas Wire Power

Wire power is the power drawn by the motor. In the case where actual blower-motor combinations are being tested for equipment acceptance, it is appropriate to make these power measurements directly (see subsection on Turbine Wire Power). The required accuracy of this measurement should be ±1 percent. When estimates of wire power are required without reference to a particular blower-motor combination, it is usually calculated from the brake power by using the appropriate efficiency.

Gas wire power is related to gas motor brake power by the motor efficiency, e_m:

$$\text{gas wire power} = \text{gas motor brake power}/e_m \tag{114}$$

where e_m is in decimal percent.

Motor efficiencies are a function of the motor and the load. Typically, full-load motor efficiencies may range from 0.90 to 0.95. If determinations of the gas wire power and gas motor brake power are made directly, then e_m can be calculated from Equation 114.

As with the other power terms, it is advisable to define a standard gas wire power. It could be defined as the standard gas brake power (standard gas motor brake power) divided by a standard motor efficiency, e_{ms}. A value of 9.92 is suggested for e_{ms}.

TURBINE PUMP POWER

Turbine (pump) power is that part of the total aeration system power requirement that is specifically related to the operation of a mechanical device such as a turbine or pump. It refers to the general class of turbine (pump) power determinations, including water, delivered, brake, and wire power. With the exception of wire power, the determinations for turbines are normally made with some type of torque measuring device. The following subsection discusses various methods used to measure shaft power.

Shaft Power Determinations

Shaft power can be determined with a number of torque measuring devices. One of the oldest is the Prony brake,[3] named after G.C.F.M. Richy, Baron de Prony (1755-1839). It measures the torque required to stop the rotation of a moving flywheel. A lever arm is attached to a braking arrangement that grips the flywheel. The restraining force required at the end of the lever arm is measured with a scale of some type. The torque is then calculated as follows:

$$T_q = Lf \qquad (115)$$

where

T_q = torque, ft-lb
L = length of the lever arm (ft)
f = force required at the end of the lever arm (lb)

The power required is related to torque and rotational speed by the following expression:

$$P = 2\pi T_q N/33,000 \qquad (116)$$

where

P = power (hp), Lf/t
N = rotational speed (rpm), t^{-1}

Using this principle, actual determinations of brake power are made with the flywheel rigidly mounted in the casing of the unit being tested, such as a motor, blower, or gear box. The unit is mounted on a gimbal, which allows it to rotate without appreciable power loss, and is operated under the desired test conditions. The torque required to stop the casing of the unit from revolving is the brake or shaft power. As might be imagined, this type of arrangement can be difficult to set up. The Prony brake is an example of a cradled dynamometer. There are other more modern devices of this type that are easier to apply.

The torque cell is another method of measuring brake power and is a type of transmission dynamometer. This method works on the principle that the strain induced in a rod or hollow cylinder is proportional to the applied torque.[3] Usually, a thin-walled metal cylinder is used as the shaft or is connected to the shaft of the unit being tested. Strain gauges attached at 45° angles on the surface of the cylinder measure the strain developed under load (multiple strain gauges may be installed and connected so that the axial and transferse loads will cancel out in the final readout circuit). The torque is related to the strain at 45° angles by:

$$T_q = (1/12)\pi\, \overline{G}(r_o{}^4 - r_i{}^4)\xi_{45}/r_o \qquad (117)$$

where:

$\overline{G}$ = shear modulus of elasticity (lb/in.^{2}), f/L^2
r_o = outside radius of the cylinder (in.), L
r_i = inside radius of the cylinder (in.), L
ξ_{45} = strain at 45° angles

Power can then be calculated by Equation 116. Other types of transmission dynamanters are also available. The required accuracy for shaft horsepower determinations should be within $\underline{+}2$ percent.

Turbine Delivered Power

For turbine equipment such as surface aerators and submerged turbines, delivered horsepower is the power required at the output shaft of the gear box to turn the shaft and impeller at the desired rotational speed in water under actual conditions. This power is also referred to as turbine shaft or turbine water power. The turbine delivered power is normally measured with a brake, torque cell, or other measuring device, although it is not usually referred to as a brake power.

As with the other power terms, it would be advisable to define a standard turbine delivered power to be used when reporting clean water data for advertising or comparison purposes. Since water temperature would seem to be the most important variable affecting the turbine power draw, it might be appropriate to define standard turbine delivered power as the turbine shaft power required at a water temperature of 68°F. While it is realized that it would be impossible to run all power tests at 68°F, it is hoped that correlations exist in the field today that might relate power draw at a given temperature to that at 68°F.

Pump Delivered Power

Pump delivered power should be calculated using the following equation:

$$\text{pump delivered horsepower} = QHS_g/3960 \qquad (118)$$

where:

Q = liquid flow rate (gpm), L^3/t
H = total pump head (ft of water), L
S_g = water specific gravity at temperature T

The flow rate, Q, should be determined from a manufacturer's H-Q curve for the pump used. The pump head, H, should be based on actual measurement and should be accurate to ±1 percent. The standard pump delivered power should be referenced to water at 68°F.

Turbine (Pump) Brake Power

The brake power associated with turbine equipment is similar to the brake power associated with gas delivery equipment. The gear box brake power is generally considered to be the shaft power associated with the input shaft. Furthermore, the motor brake power may not be the same as the gear box brake power due to the drive or coupling employed between the motor and the gear reducer (see the previous subsection on Gas Brake Bower).

In a manner similar to gas delivery devices, the gear box brake power is related to turbine delivered power by a gear box efficiency, e_g:

$$\text{turbine gear box brake power} = \text{turbine delivered power}/e_g \qquad (119)$$

where e_g is in decimal percent.

The gear box efficiency is a function of the gear box design (including the number of gear reductions) and the load. The losses in a gear box are basically of two different types, a fairly constant churning loss and a bearing loss that is a function of load. Generally speaking, these gear boxes are very efficient. Rating curves are normally available from the manufacturer. A range of full-load gear box efficiencies applicable throughout the field today might be 0.94 to 0.96. When measurements of the powers in Equation 119 are made directly the efficiency, e_g, can be calculated.

The turbine motor brake power is related to the turbine gear box brake power by the coupling or drive efficiency, e_d:

$$\text{turbine motor brake power} = \text{turbine gear box brake power}/e_d \qquad (120)$$

where e_d is in decimal percent.

The definition of the term e_g, as well as its range, is the same as that discussed in the subsection on Gas Brake Power. Again, e_d can be calculated if the powers in Equation 120 are measured directly.

As with the other power terms, it would be appropriate to define a standard turbine brake power. The standard turbine brake power could be related to the standard turbine delivered power by a standard gear box efficiency, e_{gs}, and a standard drive efficiency, e_{ds}. Possible values for both of these efficiencies might be 0.95, although many others could be proposed.

Actual measurements of either turbine motor brake power or turbine gear box brake power can be made with the methods in the Shaft Power Determinations subsection. The required accuracy on this measurement should be ±2 percent.

Turbine (Pump) Wire Power

Turbine wire power can be measured directly with a recording wattmeter. It is very important, however, that the wattmeter be zeroed and calibrated accurately before it is used. An ammeter can be used as long as the voltage and power factor are also measured. An expression for calculating 3-phase power from current, voltage, and power factor measurements is:

$$\text{wire horsepower (3 phase)} = 1.73\ Ei(PF)/746 = 2.32 \times 10^{-3}\ Ei(PF) \qquad (121)$$

where:

E = voltage (volts)
i = current (amperes)
PF = power factor

It is always appropriate to use a recorder when making power measurements. During the operation of a mechanical device, there are usually fluctuations in load that can be most easily observed with a recorder. It is recommended that all wire power measurements be made in accordance with the ASME Power Test Code and the IEEE Standard. The required accuracy of wire power measurements should be within ±1 percent.

Turbine wire power is related to turbine motor brake power by the motor efficiency, e_m:

$$\text{turbine wire power} = \text{turbine motor brake power}/e_m \qquad (122)$$

where e_m is in decimal percent.

As mentioned previously in the subsection on gas power, a range of full-load motor efficiencies might be 0.90 to 0.95. If the powers in Equation 122 are measured directly, e_m can be calculated.

As with gas power determinations, it is recommended that a standard efficiency, e_{ms}, be used to relate standard turbine wire power to standard turbine power (standard turbine motor brake power). As before, a possible value of e_{ms} might be 0.92.

TOTAL POWER

The summation of the gas and turbine powers is the total power. Thus, references can be made to total delivered power, total brake power, and total wire power. When reporting clean water power data, it would be appropriate to report the gas and turbine power data separately, as well as the combined total. In the case of data to be used for advertising or comparison purposes, all power results should be reported in terms of standard conditions.

MECHANICAL AERATOR POWER

This subsection describes the procedures to predict installed aerator power based on a single-sample field or factory test. The calculated installed power has two components, the most likely value and the range of uncertainty. The uncertainty is a function of the measuring technique and the ability to define power losses in each appropriate drive component.

In practice, a precise factory test can be as accurate as a field test. Most often the primary power is used as the basis of comparison. The results described below could also be applied to a shaft power comparison.

Measurements

Electric Power--

These measurment techniques were covered previously in this section.

Rotating Shaft Torque--

There are several manufacturers of torque measuring devices for rotating shafts. The two most common devices are inductance and strain gage torque indicators.

For measured torques at the upper limit of the instrument, the true value can be determined with ±0.3 percent. In most applications, a measurement uncertainty of ±1.5 percent is attainable.

It is possible to custom build torque instrumentation by mounting a strain gage bridge on a shaft. Precautions are required to identify slip ring noise and other errors. For example, strain gage torque measurements are subject to errors induced by bending. Therefore, care must be exercised in interpreting aerator shaft torque measurements. A custom device must have a certified calibration, similar to commercial units.

Reaction Loads--

A common method for measuring laboratory-scale power is a reaction dynamometer. The drive unit is mounted on a low friction bearing. The torque required to prevent drive rotation is equal to the impeller torque applied to the fluid plus the bearing torque. This approach can also be applied to large-scale drive units.

A related technique would involve strain gaging the drive support structure. The structural design and location of the strain gages could be optimized to indicate torque, thrust, and bending loads.

In each case, certified calibration is essential. These data must include any special corrections related to operating losses. These corrections will probably have a complex dependence on shaft speed, delivered power, shaft/impeller weight, etc.

Shaft Speed--

Speed should be measured with a tachometer or stroboscope having an accuracy of ±1 percent. For low-speed shafts, counting revolutions and measuring elapsed time should be done in a fashion yielding similar accuracy.

Power Calculations

General Relationships--

$$SHP = BHP\ \eta_R \eta_M \qquad (123)$$

$$BHP = PHP\ \eta_p \qquad (124)$$

where:

SHP = shaft power (hp), Lf/t

BHP = brake (output) power of prime mover (hp), Lf/t

PHP = prime mover power (hp), Lf/t

η_R = reducer efficiency in decimal percent

η_M = miscellaneous (bearings, etc.) efficiency of special factory hardware in decimal percent

η_p

η_p = prime mover efficiency in decimal percent

Rotating Torque Device--

$$P = 2\pi T_q N/33{,}000 = 1.904 \times 10^{-4}\ T_q N \qquad (116)$$

where:

P = power (hp), Lf/t

N = shaft speed (rpm), t^{-1}

T_q = torque (ft-lb), Lf

Reaction Load Device--

The measurements made with a reaction load device can be directly related to shaft torque. The appropriate conversion should be applied to calculate torque, T_q. Measurements should also be made with the impeller operating in air to provide an accurate estimate of zero-load torque, T_{qo}. Since the weight density difference between air and water is so great, the air-induced power on the impeller should be no more than 0.1 percent of that in water. An appreciable torque measurement, however, can be attributed to system tare. The tare or zero-load torque value should be subtracted from the torque value measured in water to calculate shaft horsepower:

$$SHP = 1.904 \times 10^{-4}\ N(T_q - T_{qo}) \qquad (125)$$

A tare calculation should not be applied for measurements of BHP or PHP. At zero load, electric motors draw 5 to 9 percent of full-load power. Current draw will be 25 to 35 percent of full-load amperes. Motor power (3 phase, a-c) is not directly proportional to the product of current and voltage since the power factor (see Equation 121) can vary significantly depending on motor load. The power factor can be obtained from the manufacturer's motor curve. Similar relations are probably available for other prime movers. Reducers and variable speed drives also have significant losses at zero-load conditions. If the calibrated efficiency curves are used, proper corrections are automatically made for unit efficiencies.

Reducer and Variable Speed Drives

Power losses for these devices can be considered as having two nearly independent components. Part of the losses are speed dependent. The second loss element is dependent on output torque or power. The total unit loss is the sum of these terms. If component efficiency has been determined as a function of speed and load, these factors are properly considered and the remainder of this subsection is not applicable.

For a gear-type reducer, power losses are separated into churning and gear loading components. Chruning losses are dependent almost exclusively on rotating speed. A slight dependence on transmitted loads is related to oil temperature changes. Gear loading losses at a specific speed are linearly dependent on delivered torque (or power).

For illustrative purposes, consider a hypotehtical reducer that is 95 percent efficient at its 100-BHP rated capacity. Thus, the mixer drive will generate 95 SHP at rated capacity. An applicable rule-of-thumb is that losses are split 50-50 between churning and gear loading. For this example, churning losses would be 2.5 hp irrespective of the magnitude of the load on the reducer. Gear loading losses, however, vary directly with output load and would only reach 2.5 hp at rated capacity. Total gear reducer losses are equal to the sum of churning and gear loading losses, which for this hypothetical unit can be calculated as:

$$\mathrm{hp}_{GR}\ \text{losses} = 2.5 + 2.5\left(\frac{\text{SHP for test aerator}}{\text{SHP at rated capacity}}\right)$$

For a factory test on a 20-SHP aerator:

$$\begin{aligned}\mathrm{hp}_{GR}\ \text{losses} &= 2.5 + 2.5(20/95)\\ &= 2.5 + 0.5\\ &= 3.0\end{aligned}$$

and:

$$BHP = SHP + \text{gear reducer losses} \quad (126)$$
$$= 20 + 3$$
$$= 23$$

Gear reducer efficiency can then be determined from Equation 119:

$$\eta_R = SHP/(BHP\ \eta_M) \quad (123)$$

Assuming $\eta_M = 1.0$:

$$\eta_R = 20/(23 \times 1.0)$$
$$= 0.87$$

The above example demonstrates the importance of specifying efficiency as a function of speed and loading. This precaution can be particularly important in a factory test where the reducer is operated well below its design point.

RECOMMENDED STANDARDIZATION

The recommended standards for power measurements made during a clean water test are shown in Tables 24 (Section 9), 25, 26, 27, and 28. It is recommended that standard power be used whenever data are to be reported for advertising or comparison purposes. The procedures for determining standard pump, gas, and turbine delivered power are summarized in Tables 26, 27, and 28, respectively. Standard pump and gas delivered power should be determined by a calculation procedure; standard turbine delivered power can be determined either by direct or indirect measurement.

Standard pump delivered power should be determined using the equation shown in Table 26. The power should be calculated for water at 68°F. The measured parameters should conform to the accuracies shown.

Standard gas delivered power should be determined using the adiabatic compression equation given in Table 27. The following standard conditions would apply:

Standard air (68°F, 14.70 psia, 36 percent relative humidity)
Diffuser headloss corrected to 68°F
Discharge line loss of 1.0 psi
Blower inlet suction loss of 0.1 psi

TABLE 25. RECOMMENDED EQUIPMENT EFFICIENCIES TO BE USED FOR STANDARD POWER DETERMINATIONS

Item	Present Efficiency Range* (decimal percent)	Recommended Standard Efficiency (decimal percent)
Compressor	0.50 - 0.80	0.70
Gear box	0.94 - 0.96	0.95
Coupling or drive	0.90 - 1.00	0.95
Motor	0.90 - 0.95 (most)	0.92

*Efficiencies quoted are for full-load conditions.

TABLE 26. STANDARD PUMP DELIVERED POWER

Pump delivered power should be calculated using the following equation:

$$\text{pump delivered power} = QHS_g/3960 \qquad (118)$$

where:

Q = liquid flow rate (gpm)

H = total pump head (ft of water)

S_g = water specific gravity at temperature T

The flow rate, Q, should be determined from a manufacturers H-Q curve for the pump used. The pump head should be based on actual measurement and should be accurate to ±1 percent. The standard pump delivered power should be referenced to water at 68°F.

The measured parameters should conform to the accuracies shown in Table 24.

Standard turbine delivered power can be determined either by direct or indirect measurement. Direct methods include cradled dynamometers and transmission dynamometers. Indirect measurements include electrical and shaft horsepower determinations made on other components in the aeration system, such as a motor, as long as the appropriate efficiencies are known. Power measurements should be related to water at 68°F, if possible. The accuracy of all wire power measurements should be within ±1 percent.

When standard brake and wire power values are determined based on

TABLE 27. STANDARD GAS DELIVERED POWER

Gas delivered power should be calculated using a variation of Equation 106 that excludes the blower, drive, and motor efficiency terms:

$$\text{gas delivered power} = [w\bar{R}T_1/(550K)][(p_2/p_1)^K - 1]$$

For air at standard conditions of 68°F, 14.70 psia, and 36 percent relative humidity, this equation reduces to:

$$\text{standard air delivered power} = 0.227\,Q_a[(p_{2s}/p_{1s})^{0.283} - 1] \quad \text{(A)}$$

where p_{2s} and p_{1s} refer to standard discharge and inlet pressures, respectively, such that:

p_{2s} = standard atmospheric pressure (14.70 psia) + actual static head (H) + standard diffuser loss at 68°F (h_L) + standard pipe loss (1.0 psia)

$$= 15.70 \text{ psia} + H + h_L\text{, and} \quad \text{(B)}$$

P_{1s} = standard atmospheric pressure (14.70 psia) - standard suction loss (0.1 psia)

$$= 14.60 \text{ psia} \quad \text{(C)}$$

Equations A, B and C are recommended for standard air delivered power. The air flow rate, Q_a, should be accurate to ±2 percent. The static head, H, and diffuser headloss, h_L, measurements should be accurate to ±1 percent and ±5 percent, respectively.

TABLE 28. STANDARD TURBINE DELIVERED POWER

Turbine delivered power (actually the turbine shaft horsepower) may be determined by direct measurement or by indirect measurement when the appropriate efficiency information is available on the motor, coupling (drive), and gear box. Standard turbine delivered power should be obtained by referencing turbine shaft power draw to water at standard conditions of temperature and pressure.

Direct Measurement

The following techniques are appropriate for the direct measurement approach:

1. Cradled dynamometers (i.e., cradled motors, generators, and Prony brakes).
2. Transmission dynamometers (i.e., surface strain types and angular twist types).

All shaft power measurements should be accurate to ±2 percent.

Indirect Measurements

The following techniques are appropriate for the indirect measurement approach:

1. Measurement gear box input shaft horsepower, knowing the gear box efficiency.
2. Measurement of motor shaft horsepower, knowing the gear box and coupling efficiencies.
3. Measurement of motor wire horsepower, knowing the gear box coupling, and motor efficiencies.
4. Other methods.

All shaft power measurements should be accurate to ±2 percent. All wire power measurements should be accurate to ±1 percent.

delivered power data, the recommended equipment efficiencies shown in Table 25 should be used. This recommendation applied to gas, pump, and turbine power. The basic relationships between delivered, brake, and wire power have been discussed previously.

For the various types of power measurements, whether for the determination of standard power or not, it is strongly recommended that the following performance codes be adhered to:

Shaft power measurement - ASME Power Test Codes #19.7, #9, and #10.[4]
Electrical power measurement - ASME Power Test Codes #19.6, #9, and #10;[4]
    IEEE Standards #5, #7, and #9.
Air flow measurement - ASME Power Test Codes #19.5, #19, and #10.
Pressure measurement - ASME Power Test Code #19.2.[4]
Temperature measurement - ASME Power Test Code #19.3.[4]
Rotary speed measurement - ASME Power Test Code #19.3.[4]

Additional reference that may prove valuable include Intersoll-Rand's _Compressed Air and Gas Data_[6] and the Compressed Air and Gas Institute's _Compressed Air and Gas Handbook_.[7]

REFERENCES

1. Fair, G.M. and J.C. Geyer, Water Supply and Wastewater Disposal, John Wiley & Sons, Inc., New York City, 1956.

2. Metcalf and Eddy, Inc., Wastewater Engineering, McGraw-Hill, New York City, 1972.

3. Holman, J.P., Experimental Methods for Engineers, McGraw-Hill, New York City, 1966.

4. ASME, Power Test Codes #9, 10, 19.2, 19.3, 19.5, 19.6, 19.7, and 19.13.

5. IEEE, Standards #5, 7, and 9.

6. Gibbs, C.W., Compressed Air and Gas Data, Ingersoll-Rand Co., Woodcliff Lake, New Jersey, 1971.

7. Compressed Air and Gas Handbook, Compressed Air and Gas Institute, New York City, Undated.

SECTION 11

PROPOSED EVALUATION PROCEDURE FOR THE RECOMMENDED CLEAN WATER OXYGEN TRANSFER TEST

The various techniques employed to date for clean water testing, data analysis, and design application of test results for oxygen transfer systems have important similarities and differences. These techniques are similar in that they all include deoxygenation, reaeration, data collection, and data analysis to estimate SOTR and OTR_f. However, subtle differences in the details of each step can markedly affect the calculated values of SOTR and OTR_f.

The ASCE Subcommittee on Oxygen Transfer Standards in this report has reviewed current practices and recommended procedures that have been judged to be the most desirable and workable for the clean water evaluation of oxygen transfer systems. The next logical step is for these recommended procedures to be tested experimentally and evaluated in practice by manufacturers, consulting engineers, and others involved in producing, specifying, testing, and using oxygen transfer systems. It is proposed that this evaluation be conducted using a two-part program. The first part would consist of an Experimental Research Evaluation, whereas the second part would consist of a Comparative Practical Evaluation. Although the parts are related and complement each other, either part could stand alone.

EXPERIMENTAL RESEARCH EVALUATION

Although the Subcommittee drew upon a wealth of talent and experience in developing recommended procedures for clean water testing, some areas of uncertainty remained and had to be handled by reasonable assumptions. Consequently, the accuracy and precision of these recommended procedures need to be comprehensively field evaluated to determine their applicability in achieving the desired goal of realistic prediction of actual oxygen transfer rates, OTR_f, under process conditions.

The Experimental Research Evaluation would evaluate the OTR_f values predicted from the clean water test by comparing them with values measured directly in both clean and process water using the radioactive tracer technique. General features of the proposed Experimental Research Evaluation are outlined in Table 29.

COMPARATIVE PRACTICAL EVALUATION

In addition to determining the accuracy of the recommended clean water test procedures as a predictor of OTR_f, it would be useful to evaluate these procedures relative to the various other methods currently in use. This evaluation could be accomplished at two levels.

One level would rely strictly on voluntary participation in the evaluation program by manufacturers and others involved in aerator testing. The voluntary participants would agree to report their results to the Subcommittee. An advantage of this level is that it could be implemented without external funding. However, there might be a tendency for some participants to withhold certain data.

Another level would place the Comparative Practical Evaluation directly under the control of the Subcommittee. In this plan, the Subcommittee would determine the techniques and devices to be compared and would retain a consultant to perform the testing. This approach would obviously require external funding and might easily be combined with work sponsored under the Experimental Research Evaluation.

It is proposed that, as a minimum, the Subcommittee pursue the voluntary level of Comparative Practical Evaluation. This activity could be coordinated by a new subgroup within the Subcommittee. Simultaneously the Subcommittee should investigate the possibility of obtaining funds for the Experimental Research Evaluation and/or the second level of the Comparative Practical Evaluation.

TABLE 29. GENERAL FEATURES OF PROPOSED EXPERIMENTAL RESEARCH EVALUATION

Test Facilities

- Small to medium size aeration systems located in operating facilities where process wastewater is available should be used.
- Total operating facility should be large enough to unload one aeration unit or tank for testing.
- Number and types of systems selected should cover various generic aeration equipment, e.g., one surface aeration system, one diffused air aeration system, and one other submerged aeration system.

Test Program

- Clean water unsteady state test should be performed according to recommended procedures.
- α, β, and θ should be measured according to recommended procedures.
- SOTR and OTR_f should be calculated using recommended methods.
- SOTR and OTR_f should be measured by radioactive tracer technique.
- OTR_f values obtained with above two methods should be compared.

Program Administration

- Program should be administered by ASCE Subcommittee on Oxygen Transfer Standards with external funding.
- Actual testing should be performed by consultants under Subcommittee direction.

APPENDIX A

NONLINEAR ESTIMATION PROGRAM

Most nonlinear least squares parameter estimation procedures involve iterative techniques for solution. The linearization method uses a Taylor series expansion of the model about some initial parameter estimates. The expansion is truncated after the first derivative, resulting in a linear approximation to the nonlinear model. Linear least squares is then applied to the approximate linear model in successive steps until convergence to the least square estimate is obtained.

For the exponential form of the oxygen transfer model, the expansion proceeds as follows. First, write the model in terms of general parameters, e.g., K_i:

$$C = K_1 - (K_1 - K_2)\exp(-K_3 t) \qquad \text{(A1)}$$

where:

$K_1 = C^*_\infty$
$K_2 = C_o$
$K_3 = K_L a'$

The partial derivatives of the model, Equation A1, with respect to the parameters are computed as:

$$Z_1 = \partial C/\partial K_1 = 1 - \exp(-K_3 t) \qquad \text{(A2a)}$$

$$Z_2 = \partial C/\partial K_2 = \exp(-K_3 t) \qquad \text{(A2b)}$$

$$Z_3 = \partial C/\partial K_3 = (t)(\exp(-K_3 t))(K_1 - K_2) \qquad \text{(A2c)}$$

The Taylor series expansion of Equation A1 about the parameters K_i then becomes:

$$C_{obs} = C^o{}_{calc} + Z_1^o(K_1 - K_1^o) + Z_2^o(K_2 - K_2^o) + Z_3^o(K_3 - K_3^o) \qquad \text{(A3)}$$

where:

C_{obs} = the observed DO concentration value,

C^o_{calc} = the calculated DO concentration value using the parameter values K^o_i,

and the superscript (^{o}) indicates the values of the parameters about which the expansion occurs.

Equation A3 can be written in the following linear form:

$$W^o = b_1 Z^o_1 + b_2 Z^o_2 + b_3 Z^o_3 \tag{A4}$$

where:

$W^o = C_{obs} - C^o_{calc}$

$b_i = K_i - K^o_i$

Z^o_i = the partial derivatives of the model evaluated at the parameter values K^o_i

To begin the estimation procedure, initial values of the model parameters, K^o_i, must be provided. These initial parameter values are used to calculate the values W^o and Z^o_i in Equation A4. Because Equation A4 is linear in the parameters b_i, the linear least squares technique is used to calculate estimates of b_i. The least squares estimates of b_i provide updated estimates of the model parameters, K_i, by the following relationship:

$$K_i = b_i + K^o_i \tag{A5}$$

where K^o_i are the prior estimates of the model parameters and K_i are the updated estimates. The values of b_i can be viewed as corrections applied to the prior estimates of the model parameters.

The estimation procedure continues. The new values of K_i are used to calculate new values of Z_i and W_i in Equation A4. The linear least squares estimates of b_i (Equation A4) are used to provide the next update for the model parameters (Equation A5). This iterative calculation continues until the values of the model parameters converge. For models that are only moderately nonlinear, this linearization estimation procedure usually works quite well and convergence will be obtained in a few iterations.

SOLUTION OF THE NORMAL EQUATIONS

For the linearization method to work, the least squares estimates of b_i in Equation A4 must be obtained. Omitting the superscripts, the sum of squares function, S, to be minimized is:

$$S = \sum_{\text{data}} (W - b_1 Z_1 - b_2 Z_2 - b_3 Z_3)^2 \tag{A6}$$

where the summation is performed over all the data values of concentration versus time. Minimization of S with respect to the parameters b_i leads to the following set of normal equations:

$$b_1\sum Z_1^2 + b_2\sum Z_1Z_2 + b_3\sum Z_1Z_3 = \sum WZ_1 \tag{A7a}$$

$$b_1\sum Z_1Z_2 + b_2\sum Z_2^2 + b_3\sum Z_2Z_3 = \sum WZ_2 \tag{A7b}$$

$$b_1\sum Z_1Z_3 + b_2\sum Z_2Z_3 + b_3\sum Z_3^2 = \sum WZ_3 \tag{A7c}$$

Equations A7a, b, and c can be written in more compact form as:

$$a_{11}b_1 + a_{12}b_2 + a_{13}b_3 = c_1 \tag{A8a}$$

$$a_{21}b_1 + a_{22}b_2 + a_{23}b_3 = c_2 \tag{A8b}$$

$$a_{31}b_1 + a_{32}b_2 + a_{33}b_3 = c_3 \tag{A8c}$$

where:

$a_{11} = \sum Z_1^2$

$a_{12} = a_{21} = \sum Z_1Z_2$

$a_{13} = a_{31} = \sum Z_1Z_3$

$a_{22} = \sum Z_2^2$

$a_{23} = a_{32} = \sum Z_2Z_3$

$a_{33} = \sum Z_3^2$

$c_1 = \sum WZ_1$

$$c_2 = \sum WZ_2$$

$$C_3 = \sum WZ_3$$

Solution of Equations A8a, b, and c by forward elimination and back substitution yields the following equations for the least squares estimates of b_1, b_2, and b_3:

$$b_3 = (d_1d_2 - d_3d_5)/(d_1d_4 - d_3d_3) \tag{A9a}$$

$$b_2 = (d_5 - d_3b_3)/d_1 \tag{A9b}$$

$$b_1 = (c_1 - a_{12}b_2 - a_{13}b_3)/a_{11} \tag{A9c}$$

where the values of d are given by:

$$d_1 = a_{22}a_{11} - a_{12}a_{12}$$

$$d_2 = a_{11}c_3 - a_{13}c_1$$

$$d_3 = a_{11}a_{23} - a_{13}a_{12}$$

$$d_4 = a_{11}a_{33} - a_{13}a_{13}$$

$$d_5 = a_{11}c_2 - a_{12}c_1$$

CONVERGENCE

Once the least squares estimates of b_i are computed (Equations A9), the updated values of the model parameters, K_i, are calculated as follows:

$$K_i = b_i + K_i^o \tag{A5}$$

If the new values of K_i are within some specified tolerance of the prior values, then the solution is assumed to have converged and iteration stops. If the new values are not within tolerance, then the iterations continue with the new parameter values serving as the point of the next Taylor series expansion of the model.

STANDARD DEVIATIONS

Estimates of the precision (standard deviation) of the least squares parameter estimates can be obtained. These values are computed from the inverse of the coefficient matrix (A-matrix) of the linearized form of the model (Equation A8) and the residual mean square. The equations for this calculation are given below:

$$\mathrm{Var}(K_1) = (E_{11}/D)(\mathrm{RMS}) \qquad \text{(A10a)}$$

$$\mathrm{Var}(K_2) = (E_{22}/D)(\mathrm{RMS}) \qquad \text{(A10b)}$$

$$\mathrm{Var}(K_3) = (E_{33}/D)(\mathrm{RMS}) \qquad \text{(A10c)}$$

where:

$\mathrm{Var}(K_i)$ = variance of the parameters, K_i

E_{ii} = cofactors of a_{ii} in the coefficient matrix

D = determinant of the coefficient matrix

RMS = residual mean square from the fitted model

The standard deviations of the parameter estimates are obtained from the square root of the variances in Equations A10.

FORTRAN PROGRAM

The FORTRAN computer program that follows in this appendix is a nonlinear estimation of the parameters in the exponential form of the oxygen transfer model. The program uses the Taylor series linearization method and is in two parts. For greatest user ease, the computational and output portions are written in subroutine form (subroutine KLANL). The user-supplied MAIN program serves as an interface between the system constraints of the user's computer and the regression computational algorithm in the subroutine.

The MAIN program must perform the following tasks. A sample MAIN program is shown in the FORTRAN listing:

1. Read in the data to be fitted: concentration (C) versus time (T).
2. Read in initial parameter estimates (CS, CO, XKLA).
3. Provide a descriptive name for the data set (INAME).
4. Provide the logical device number for output (NOUT).

Subroutine KLANL performs all the computations for the nonlinear estimation and controls the output of the results. The notation in the subroutine is consistent with that in this appendix. The estimation and output proceeds in the following steps:

1. Write titles, name of data set, and headings for the iterations.
2. Initialize internal variables, and compute the fitted values and residual sum of squares based on the initial parameter estimates.
3. Set up the normal equations using current parameter estimates.
4. Solve normal equations for the corrections to the parameter estimates.
5. Update parameter estimates and calculate new fitted values and residual sum of squares.
6. Test for convergence. The convergence criteria are:
    a. Relative change in parameters less than 0.00001.
    b. Relative change in sum of squares less than 0.000001.
    c. The algorithm will also exit from the iteration loop if more than 10 iterations are required for convergence. A diagnostic message is printed.
7. Calculate the estimated standard deviations of the model parameters.
8. Write out a summary of the data, fitted values (F), and residuals(R).

An example estimation problem follows the FORTRAN listing.

FORTRAN COMPUTER PROGRAM

```
C
C        MAIN PROGRAM FOR NONLINEAR ESTIMATION OF OXYGEN
C                TRANSFER PARAMETERS
C
         DIMENSION C(100),T(100),F(100),R(100)
         WRITE(5,1)
1        FORMAT('  NAME OF INPUT DATA FILE:  ' $)
         READ(5,2) INAME
2        FORMAT(A5)
         OPEN(UNIT=20,MODE='ASCII',ACCESS='SEQIN',FILE=INAME)
         READ(20,10) CS,CO,XKLA
10       FORMAT(3F)
         N=1
15       READ(20,10,END=19) T(N),C(N)
         N = N+1
         GO TO 15
19       CONTINUE
         NOB = N-1
         NOUT = 5
         CALL KLANL(C,T,F,R,NOB,CS,CO,XKLA,INAME,NOUT)
         CALL EXIT
         END
C
C        SUBROUTINE KLANL PERFORMS NONLINEAR ESTIMATION COMPUTATIONS
C                AND CONTROLS OUTPUT SUMMARIES
C
         SUBROUTINE KLANL(C,T,F,R,NOB,CS,CO,XKLA,INAME,NOUT)
         DIMENSION C(100),T(100),F(100),R(100)
         REAL K1,K2,K3
C
C        STEP 1 - WRITE TITLES
C
         WRITE(NOUT,20) INAME
20       FORMAT(//20X,'NON LINEAR ESTIMATION'/
         115X,'UNSTEADY STATE OXYGEN TRANSFER'/
         223X,'DATA SET ',A5)
         WRITE(NOUT,21)
21       FORMAT(///' ITERATION',29X,'KLA',8X,'SUM OF'/
         12X,'NUMBER',6X,'C-STAR',6X,'C-ZERO',6X,'PRIME',6X,'SQUARES'/)
C
C        STEP 2 - INITIALIZATION OF VARIABLES
C


         K=0
         OSSQ = 0.0
         DO 50 I-1,NOB
         F(I) = CS-(CS-CO)*EXP(-XLA*T(I))
         R(I) = C(I) - F(I)
50       OSSQ = OSSQ + R(I)*R(I)
         WRITE(NOUT,30) K,CS,CO,XKLA,OSSQ
99       K=K+1
         A11=0.0
         A12=0.0
         A13=0.0
```

```
      A22=0.0
      A23=0.0
      A33=0.0
      C1=0.0
      C2=0.0
      C3=0.0
      SSQ=0.0
C
C      STEP 3 - SET UP NORMAL EQUATIONS FOR LINEARIZED MODEL
C              USING CURRENT LEAST SQUARES ESTIMATES.
C
      DO 100 I=1,NOB
      Z2=EXP(-XKLA*T(I))
      Z1=1.0-Z2
      Z3 = T(I)*Z2*(CS-CO)
      A11 = A11 + Z1*Z1
      A12 = A12 + Z1*Z2
      A13 = A13 + Z1*Z3
      A22 = A22 + Z2*Z2
      A23 = A23 + Z2*Z3
      A33 = A33 + Z3*Z3
      F(I) = CS - (CS-CO)*Z2
      R(I) = C(I) - F(I)
      C1 = C1 + R(I)*Z1
      C2 = C2 + R(I)*Z2
      C3 = C3 + R(I)*Z3
100   CONTINUE
C
C      STEP 4 - SOLUTION OF NORMAL EQUATIONS FOR CORRECTIONS TO
C              THE PRIOR LEAST SQUARES ESTIMATES
C
      D1 = A11*A22 - A12*A12
      D2 = A11*C3 - A13*C1
      D3 = A11*A23 - A13*A12
      D4 = A33*A11 - A13*A13
      D5 = A11*C2 - A12*C1
      BN3 = D1*D2 - D3 *D5
      BD3 = D1*D4 - D3*D3
      B3 = BN3/BD3
      BN2 = D5 - D3*B3
      B2 = BN2/D1
      B1 = (C1 - A12*B2 - A13*B3)/A11
C
C      STEP 5 - UPDATE ESTIMATES, SUM OF SQUARES
C
      K1 = B1 + CS
      K2 = B2 + CO
      K3 = B3 + XKLA
      DO 120 I=1,NOB
      F(I) = K1 -(K1-K2)*EXP(-K3*T(I))
      R(I) = C(I) - F(I)
120   SSQ = SSQ + R(I)*R(I)
C
```

```
C         STEP 6 - TEST FOR CONVERGENCE - PARAMETERS
C
          IF(B1/K1.GE.0.00001) GO TO 200
          IF(B2/K2.GE.0.00001) GO TO 200
          IF(B3/K3.GE.0.00001) GO TO 200
C
C         ITERATIONS CONVERGED
C
 150      WRITE(NOUT,30) K,K1,K2,K3,SSQ
 30       FORMAT(3X,I4,3X,4E12.4)
          GO TO 300
C
C         PARAMETERS NOT CONVERGED, TEST SUM OF SQUARES
C
 200      IF(ABS((OSSQ-SSQ).LE.0.000001) GO TO 150
C
C         SUM OF SQUARES NOT CONVERGED, TEST ITERATIONS
C
          IF(K.GT.10) GO TO 350
          WRITE(NOUT,30) K,K1,K2,K3,SSQ
C         NEW ESTIMATES
          CS = K1
          CO = K2
          XKLA = K3
          OSSQ = SSQ
          GO TO 99
 300      CONTINUE
          XDF = NOB - 3
          RSM = SSQ/XDF
          ERROR = SQRT(RSM)
          WRITE(NOUT),22) ERROR
 22       FORMAT(/' ESTIMATE OF ERROR FROM RESIDUAL MEAN SQUARE  ',F6.2)
          WRITE(NOUT,23)
 23       FORMAT(//17X,'STANDARD DEVIATIONS'/
          116X,'OF PARAMETER ESTIMATES'//)
C
C         STEP 7 - COMPUTE STANDARD DEVIATIONS OF THE PARAMETER ESTIMATES
C
          DETP = A11*A22*A33 + 2.0*A12*A13*A23
          DETN = A11*A23*A23 + A22*A13*A13 + A33*A12*A12
          DET = DETP-DETN
          E11 = A22*A33 - A23*A23
          E22 = A11*A33 - A13*A13
          E33 = A11*A22 - A12*A12
          VARK1 = (E11/DET)*RSM
          VARK2 = (E22/DET)*RSM
          VARK3 = (E33/DET)*RSM
          SIGCS = SQRT(VARK1)
          SIGCO = SQRT(VARK2)
          SIGKL = SQRT(VARK3)
          WRITE(NOUT,31) SIGCS,SIGCO,SIGKL
```

```
31      FORMAT(' ABSOLUTE'/3X'UNITS',2X,3E12.4)
        SIGCS = SIGCS/CS*100.0
        SIGCO = SIGCO/CO*100.0
        SIGKL = SIGKL/XKLA*100.0
        WRITE(NOUT,32) SIGCS,SIGCO,SIGKL
32      FORMAT(/' PER CENT'/2X'OF LSE',2X,3F12.1)
C
C       STEP 8 - WRITE FINAL SUMMARY
C
        WRITE(NOUT,33)
33      FORMAT(//15X,'SUMMARY OF DATA'//
        110X,'TIME',6X,'CONC',5X,'FITTED',3X,'RESIDUAL'/
        230X,'VALUE'/)
        DO 370 I=1,NOB
370     WRITE(NOUT,34) I,T(I),C(I),F(I),R(I)
34      FORMAT(I5,4F10.2)
        GO TO 400
350     WRITE(NOUT,35)
35      FORMAT(//3X,'SOLUTION NOT CONVERGED IN 10 ITERATIONS!'//)
400     RETURN
        END
```

EXAMPLE ESTIMATION PROBLEM

```
FORTRAN:  KLANLN
MAIN.
KLANL
LINK:    Loading
CLNKXCT KLANLN execution

 NAME OF INPUT DATA FILE:  COMB

                          NON LINEAR ESTIMATION
                    UNSTEADY STATE OXYGEN TRANSFER
                             DATA SET COMB

ITERATION                                      KLA            SUM OF
 NUMBER        C-STAR        C-ZERO           PRIME           SQUARES

     0       0.1200E+01   0.5000E+00   0.1500E+00   0.4893E+02
     1       0.1116E+02   0.1935E+01   0.6928E-01   0.6109E+01
     2       0.1133E+02   0.1186E+01   0.8733E-01   0.7795E-01
     3       0.1143E+02   0.1122E+01   0.8691E-01   0.1617E-01
     4       0.1143E+02   0.1122E+01   0.8692E-01   0.1617E-01
     5       0.1143E+02   0.1122E+01   0.8692E-01   0.1617E-01

ESTIMATE OF ERROR FORM RESIDUAL MEAN SQUARE       0.03

                          STANDARD DEVIATIONS
                         OF PARAMETER ESTIMATES

ABSOLUTE
  UNITS      0.1822E-01   0.3769E-01   0.6443E-03

PER CENT
 OF LSE             0.2          3.4          0.7

                            SUMMARY OF DATA

               TIME         CONC               FITTED            RESIDUAL
                                                VALUE

 1             2.00         2.77                2.77               0.00
 2             4.00         4.15                4.15               0.00
 3             6.00         5.35                5.31               0.04
 4             8.00         6.25                6.29              -0.04
 5            10.00         7.08                7.11              -0.03
 6            12.00         7.80                7.80               0.00
 7            14.00         8.34                8.37              -0.03
 8            16.00         8.85                8.86              -0.01
 9            18.00         9.28                9.27               0.01
10            20.00         9.62                9.61               0.01
11            22.00         9.93                9.90               0.03
12            25.00        10.24               10.25              -0.01
13            30.00        10.70               10.67               0.03
14            35.00        11.00               10.93               0.07
15            40.00        11.14               11.11               0.03
16            45.00        11.20               11.22              -0.02
17            50.00        11.25               11.29              -0.04
18            55.00        11.30               11.34              -0.04
```

APPENDIX B

BASIC NONLINEAR ESTIMATION PROGRAM

This appendix presents the BASIC computer language adaptation of the FORTRAN nonlinear estimation program discussed in Appendix A. Also given are examples of output obtained by applying the BASIC program to typical data sets using an Apple II Microcomputer.

```
10  D$ =  CRR$ (4)
20   REM
30   REM  NON-LINEAR LEAST SQUARES PROGRAM IN APPLE II BASIC
40   REM  FOR OXYGEN TRANSFER PARAMETERS
50   REM  OUTPUT SETUP FOR 40 POSITION CRT/MONITOR
60   TEXT : CALL  - 936: REM  CLEARS SCREEN
70   REM
80   REM  ::::::::::::::::::::::
90   REM  STEP 1
100   REM  WRITE TITLES
110   REM  ::::::::::::::::::::::
120   REM
130   PRINT "****************************************"
140   PRINT "        NON-LINEAR ESTIMATION FOR"
150   PRINT "     UNSTEADY-STATE OXYGEN TRANSFER"
160   PRINT "****************************************"
170   PRINT "                  BY"
180   PRINT "LINFIELD C. BROWN & GEORGE R. FISETTE"
190   PRINT "VERSION  1.0-NOVEMBER 11, 1979"
200   PRINT
210   INVERSE : PRINT "THE VALUES ARE TRUNCATED": PRINT "AND NOT ROUNDED OFF."
RINT  : NORMAL
220   REM
230   REM  PROGRAM HAS MAXIMUM LIMIT OF 30 DATA POINTS
240   REM
250   DIM C(30),T(30),F(30),R(30)
260   INPUT "IS DATA IN DISK FILE;Y/N?";A$
270   INPUT "INPUT NAME OF DATE FILL?";N$
280   IF A$ = " " GOTO 650: REM  GET DATA FROM DISK FILL
290   INPUT "DO YOU  ANT INPUT DATA SAVED ON DISK,Y/N?";A$
300   PRINT "INPUT DATA IN TIME,DO DATA PAIRS"
310   PRINT "INPUT 999,999 AS LAST DATA PAIR"
320   FOR I = 1 TO 30
330   INPUT T(I),C(I)
340   IF T(I) = 999.0 GOTO 360
350   NEXT I
360  ND = I - 1.0
370   INPUT "BEST ESTIMATE FOR C-STAR OR USE 10.0 MG/L?";CS
380   INPUT "BEST ESTIMATE FOR C-ZERO OR USE 0.0 MG/L?";CO
390   INPUT "BEST ESTIMATE FOR KLA-PRIME OR USE 4.0 1/HR?";XK
400  XK = XK / 60.0
410   IF A$ = "N" GOTO 790
420   REM
430   REM  WRITE DATA TO DISK FILE
440   REM  SPECIFIC FOR APPLE/MICROSOFT BASIC
450   REM
460   PRINT D$;"OPEN "N$;",VO,L15"
470   FOR I = 1 to ND
480   PRINT D$;"WRITE "N$;",BO,R";I
490   PRINT T(I): PRINT C(I)
500   NEXT I
510   PRINT D$;"WRITE "N$;",BO,RO"
520   PRINT ND
530   PRINT D$;"WRITE "N$;",BO,R";ND + 1.
540   PRINT CS
```

```
550   PRINT D$;"WRITE "N$;",BO,R";ND + 2.
560   PRINT CO
570   PRINT D$;"WRITE "N$;",BO,R";ND + 3.
580   PRINT XK
590   PRINT D$;"CLOSE "N$
600   GOTO 790
610   REM
620   REM  READ DISK FILE FOR DATA
630   REM  SPECIFIC FOR APPLE/MICROSOFT BASIC
640   REM
650   PRINT D$;"OPEN "N$;",VO,L15"
660   PRINT D$;"READ "N$;",BO,RO"
670   INPUT ND
680   FOR I = 1 TO ND
690   PRINT D$;"READ "N$;",BO,R";I
700   INPUT T(I),C(I)
710   NEXT I
720   PRINT D$:"READ "N$;",BO,R";ND + 1.
730   INPUT CS
740   PRINT D$;"READ "N$;",BO,R";ND + 2.
750   INPUT CO
760   PRINT D$;"READ "N$;",BO,R";ND + 3.
770   INPUT XK
780   PRINT D$;"CLOSE "N$
790   PRINT : FLASH : INPUT "HIT RETURN FOR ITERATIONS.";I$: NORMAL
800   CALL    936: PRINT : PRINT "           DATA SLT ";N$: PRINT
810   PRINT "ITERATION" TAB( 11)"C-STAR" TAB( 18)"C-ZERO" TAB( 26)"KLA" TAB ( 33)"
SUM OF"
820   PRINT TAB( 2)"NUMBER" TAB( 26)"PRIME" TAB( 33)"SQUARES"
830   PRINT TAB ( 11)"(MG/L)" TAB( 18)"(MG/L)" TAB ( 26)"(1/HR"
840   PRINT
850   REM
860   REM  ::::::::::::::::::::::
870   REM  STEP 2
880   REM  INITIALIZATION OF VARIABLES
890   REM  DO ITERATION CALCULATIONS
900   REM  ::::::::::::::::::::::
910   REM
920   K% = 0
930   OS = 0.0
940   FOR I = 1 TO ND
950  F(I) = CS - (CS - CO) * EXP ( - XK * T(I))
960  R(I) = C(I) - F(I)
970  OS = OS + R(I) * R(I)
980   NEXT I
990  ZZ$ = STR$ (CS) :VA = 5.: GOSUB 2900
1000  CS$ = ZZ$:ZZ$ = STR$ (CO): GOSUB 2900
1010  CO$ = ZZ$:ZZ$ = STR$ (XK * 60.): GOSUB 2900
1020  XK$ = ZZ$:ZZ$ = STR$ (OS): GOSUB 2900
1030  OS$ = ZZ$
1040   PRINT TAB( 4)K% TAB( 10)CS$ TAB( 18)CO$ TAB( 26)XK$ TAB( 33)OS$
1050   GOTO 1070
1060   REM
1070   REM  CALCULATION LOOP - INITILIZE VARIABLES
```

```
1080   REM
1090  K% = K% + 1
1100  A1 = 0.0
1110  A2 = 0.0
1120  A3 = 0.0
1130  A4 = 0.0
1140  A5 = 0.0
1150  A6 = 0.0
1160  C1 = 0.0
1170  C2 = 0.0
1180  C3 = 0.0
1190  SQ = 0.0
1200   REM
1210   REM  ::::::::::::::::::::::
1220   REM  STEP 3
1230   REM  SETUP NORMAL EQUATIONS FOR LINEARIZED MODEL
1240   REM  USING CURRENT LEAST SQUARE ESTIMATES
1250   REM  ::::::::::::::::::::::
1260   REM
1270   FOR I = 1 TO ND
1280  Z2 = EXP ( - XK * T(I))
1290  Z1 = 1.0 - Z2
1300  Z3 = T(I) * Z2 * (CS - CO)
1310  A1 = A1 + Z1 * Z1
1320  A2 = A2 + Z1 * Z2
1330  A3 = A3 + Z1 * Z3
1340  A4 = A4 + Z2 * Z2
1350  A5 = A5 + Z2 * Z3
1360  A6 = A6 + Z3 * Z3
1370  F(I) = CS - (CS - CO) * Z2
1380  R(I) = C(I) - F(I)
1390  C1 = C1 + R(I) * Z1
1400  C2 = C2 + R(I) * Z2
1410  C3 = C3 + R(I) * Z3
1420   NEXT I
1430   REM
1440   REM  ::::::::::::::::::::::
1450   REM  STEP 4
1460   REM  SOLUTION OF NORMAL EQUATIONS FOR CORRECTIONS
1470   REM  TO THE PRIOR LEAST SQUARES ESTIMATES
1480   REM  ::::::::::::::::::::::
1490   REM
1500  D1 = A1 * A4 - A2 * A2
1510  D2 = A1 * C3 - A3 * C1
1520  D3 = A1 * A5 - A3 * A2
1530  D4 = A6 * A1 - A3 * A3
1540  D5 = A1 * C2 - A2 * C1
1550  XN = D1 * D2 - D3 * D5
1560  XD = D1 * D4 - D3 * D3
1570  X3 = XN / XD
1580  YN = D5 - D3 * X3
1590  X2 = YN / D1
1600  X1 = (C1 - A2 * X2 - A3 * X3) / A1
1610   REM
```

```
1620   REM  ::::::::::::::::::::::
1630   REM  STEP 5
1640   REM  UPDATE ESTIMATES, SUM OF SQUARES
1650   REM  ::::::::::::::::::::::
1660   REM
1670  T1 = X1 + CS
1680  T2 = X2 + CO
1690  T3 = X3 + XK
1700   FOR I = 1 TO ND
1710  F(I) = T1 - (T1 - T2) * EXP ( - T3 * T(I))
1720  R(I) = C(I) - F(I)
1730  SQ = SQ + R(I) * R(I)
1740   NEXT I
1750   REM
1760   REM  ::::::::::::::::::::::
1770   REM  STEP 6
1780   REM  TEST FOR CONVERGENCE - PARAMETERS   1 PART IN 100,000
1790   REM  :::::::::::::::::::::
1800   REM
1810   IF (X1 / T1 ≥ 0.00001) AND (X2 / T2 ≥ 0.00001) AND (X3 / T3 ≥ 0.00001) GOT
0 2160
1820   REM
1830   REM  PARAMETERS NOT CONVERGED,
1840   REM  TEST SUM OF SQUARES - 1 PART IN 1,000,000
1850   REM
1860   IF ABS ((OS - SQ) / SQ)  ≤ 0.000001 GOTO 2160
1870   REM
1880   REM  SUM OF SQUARES NOT CONVERGED,
1890   REM  TEST NO. OF ITERATIONS
1900   REM
1910   IF (K% > 10) GOTO 2090
1920  ZZ$ = STR$ (T1) : GOSUB 2900
1930  T1$ = ZZ$:ZZ$ =  STR$ (T2) : GOSUB 2900
1940  T2$ = ZZ$:ZZ$ =  STR$ (T3  * 60.): GOSUB 2900
1950  T3$ = ZZ$:ZZ$ =  STR$ (SQ) : GOSUB 2900
1960  SQ$ = ZZ$
1970   PRINT TAB( 4)K% TAB( 10)T1$ TAB( 18)T2$ TAB( 26)T3$ TAB( 33)SQ$
1980   REM
1990   REM  NEW ESTIMATES
2000   REM
2010  CS = T1
2020  CO = T2
2030  XK = T3
2040  OS = SQ
2050   GOTO 1090
2060   REM
2070   REM  OUTPUTS
2080   REM
2090   PRINT
2100   PRINT "SOLUTION NOT CONVERGED IN 10 ITERATIONS'"
2110   PRINT  "CHANGE VALUE IN LINE 2670 to TRY MORE  ITERATIONS."
2120   END
2130   REM
2140   REM  OUTPUT PARAMETER ESTIMATES
```

```
2150  REM
2160  ZZ$ =  STR$ (T1): GOSUB 2900
2170  T1$ = ZZ$:ZZ$ = STR$ (T2): GOSUB 2900
2180  T2$ = ZZ$:ZZ$ = STR$ (T3 * 60.): SOSUB 2900
2190  T3$ = ZZ$:ZZ$ = STR$ (SQ): GOSUB 2900
2200  SQ$ = ZZ$
2210   PRINT TAB( 4)K% TAB( 10)T1$ TAB( 18)T2$ TAB( 26)T3$ TAB( 33)SQ$
2220   PRINT
2230   REM
2240   REM  ::::::::::::::::::::::
2250   REM  STEP 7
2260   REM   COMPUTE STANDARD DEVIATIONS OF PARAMETER ESTIMATES
2270   REM  ::::::::::::::::::::::
2280   REM
2290  XF = ND - 3.0
2300  RS = SQ / XF
2310  BR = SQR (RS)
2320   PRINT "STD DEVIATIONS OF PARAMETER ESTIMATES"
2330   PRINT
2340  DP = A1 * A4 * A6 + 2.0 * A2 * A3 * A5
2350  DN = A1 * A5 * A5 + A4 * A3 * A3 + A6 * A2 * A2
2360  DT = DP - DN
2370  F1 = A4 * A6 - A5 * A5
2380  F2 = A1 * A6 - A3 * A3
2390  F3 = A1 * A4 - A2 * A2
2400  V1 = (F1 / DT) * RS
2410  V2 = (F2 / DT) * RS
2420  V3 = (F3 / DT) * RS
2430  S1 = SQR (V1)
2440  S2 = SQR (V2)
2450  S3 = SQR (V3)
2460  ZZ$ = STR$ (S1):VA = 5.: GOSUB 2900
2470  S1$ = ZZ$:ZZ$ = STR$ (S2): GOSUB 2900
2480  S2$ = ZZ$:ZZ$ = STR$ (S3 * 60.): GOSUB 2900
2490  S3$ = ZZ$
2500   PRINT " UNITS" TAB( 10)S1$ TAB( 18)S2$ TAB( 26)S3$
2510  S1 = S1 / CS * 100.0
2520  S2 = S2 / CO * 100.0
2530  S3 = S3 / XK * 100.0
2540  ZZ$ = STR$ (S1):VA = 3.: GOSUB 2900
2550  S1$ = ZZ$:ZZ$ = STR$ (S2): GOSUB 2900
2560  S2$ = ZZ$:ZZ$ = STR$ (s3): GOSUB 2900
2570  S3$ = ZZ$
2580   PRINT "% OF LSE" TAB( 10)S1$ TAB( 18)S2$ TAB( 26)S3$
2590   PRINT
2600  ZZ$ = STR$ (ER):VA = 4.: GOSUB 2900
2610  ER$ = ZZ$
2620   PRINT "ESTIMATE OF ERROR = ";FR$
2630   REM
2640   REM  ::::::::::::::::::::::
2650   REM  STEP 8
2660   REM  WRITE SUMMARY
2670   REM  ::::::::::::::::::::::
2680   REM
2690   PRINT
2700   FLASH : INPUT "HIT RETURN FOR SUMMARY OF DATA.";I$: NORMAL
```

```
2710   CALL - 936: PRINT : PRINT : REM  CLEARS SCREEN
2720   PRINT TAB( 13)"SUMMARY OF DATA"
2730   PRINT : PRINT
2740   PRINT TAB( 8)"TIME" TAB( 16)"CONC" TAB( 22)"FIT VALUE" TAB( 32)"RESIDUAL"
2750   PRINT TAB( 8)"(MIN)" TAB( 15)"(MG/L)" TAB( 23)"MG/L"
2760   PRINT
2770   FOR I = 1 TO ND
2780  ZZ$ = STR$ (F(I)):VA = 4.: GOSUB 2900
2790  H1$ = ZZ$:ZZ$ = STR$ (R(I)): GOSUB 2900
2800  H2$ = ZZ$
2810   PRINT TAB( 2)I TAB( 8)T(I) TAB( 16)C(I) TAB( 25)H1$ TAB( 33)H2$
2820   NEXT I
2830   PRINT : PRINT
2840   PRINT "****************************************"
2850   END
2860   REM
2870   REM  OUTPUT FORMATTING ROUTINES
2880   REM  SPECIFIC FOR APPLE/MICROSOFT BASIC
2890   REM
2900  LL = LEN (ZZ$)
2910   IF LL< 12 THEN ZZ$ = LEFT$ (ZZ$,VA): RETURN
2920   IF  MID$ (ZZ$,LL - 2,1) = "+" THEN ZZ$ = LEFT$ (ZZ$,VA - 3) + RIGHT$ (ZZ
$ 3):  RETURN
2930  CC = 2.: IF LEFT$ (ZZ$,1)   =   "-" THEN CC = 1.
2940   IF MID$ (ZZ$,LL - 3,1) = "R" THEN RL = VAL (RIGHT$ (ZZ$,2)):NN$ = MID$
 (ZZ$,CC,1): FOR J = 1 TO BE:NN$ = "O" + NN$:: NEXT J:ZZ$ = "." NN$ + MID$ (Z
Z$,CC + 2,LL - 4): IF CC = 2. THEN ZZ$ = "-" + ZZ$
2950  ZZ$ = LEFT$ (ZZ$,VA): RETURN
2960   REM
2970   REM  NON-LINEAR LEAST SQUARES PROGRAM FOR
2980   REM  UNSTEADY-STATE OXYGEN TRANSFER
2990   REM  LY LINFIELD C. BROWN & GEORGE R. FISETTE
3000   REM  VERSION  1.0-NOVEMBER 11, 1979
3010   REM  COPYRIGHT BY ASCE
```

```
RUN
********************************************************************************
            NON-LINEAR ESTIMATION FOR UNSTEADY-STATE OXYGEN TRANSFER
********************************************************************************
BY
LINFIELD C. BROWN & GEORGE R. FISETTE
VERSION  1.0-NOVEMBER 11, 1979

IS DATA IN DISK FILE; Y/NPY
INPUT NAME OF DATA FILE?TEST2

                                DATA SET TEST2

ITERATION       C-STAR           C-ZERO          KLA           SUM OF
NUMBER                                           PRIME         SQUARES
0               10               .1              .07           .869733335
1               10.1592458       .713872799      .0601645437   .189522011
2               10.1889055       .694460338      .0603440105   .185289531
3               10.1893432       .694630637      .0603354201   .185289365

STANDARD DEVIATIONS OF PARAMETER ESTIMATES

ABSOLUTE UNITS  .195594007       .111803446      3.18746727E-03
PERCENT OF LSE  1.91967633       16.0993277      5.28216013

ESTIMATE OF ERROR = .152187945

SUMMARY OF DATA

                TIME             CONC            FIT VALUE      @ RESIDUAL
1               .77              1.25            1.12564889       .124351112
2               1.75             1.75            1.64603691       .103963087
3               2.67             2.05            2.10734213      -.0573421288
4               5.08             3               3.20108643      -.201086428
5               7.77             4.1             4.24803791      -.148037907
6               10.65            5.25            5.19571448       .0542855244
7               13.3             5.85            5.93358056      -.0835805573
8               17.88            7.1             6.96110108       .138898922
9               23.4             8.1             7.87555468       .224445321
10              34.52            8.9             9.00645823      -.106458228
11              49.13            9.65            9.69943839      -.0494383909

********************************************************************************
```

APPENDIX C

ALPHA-BETA TEST PROCEDURE

EQUIPMENT AND CHEMICALS

Equipment

Test Apparatus --

The required test apparatus consists of two non-metallic tanks each with a liquid capacity of 35 gal, 18 in. in diameter by 48 in. high; two air flow meters equal to Dwyer Model RMC-102-SSV (10-100 scfh); two air spargers with four 1/8-in. orifices (spargers may be constructed of 1/2-in. stainless steel pipe); plastic tubing for air piping; and an air supply source. A schematic of the test apparatus is presented in Figure C-1.

DO Apparatus --

Fast response DO probes and a DO analyzer, such as Weston & Stack Model 3000 S6A analyzer with Model 60 DO probes and Model 18 agitator, are required. DO may also be determined using the Azide Modified Winkler procedure.

Wet Chemistry Apparatus --

All necessary laboratory equipment for DO, pH, and temperature determinations of grab samples taken from the aeration tanks shall be provided.

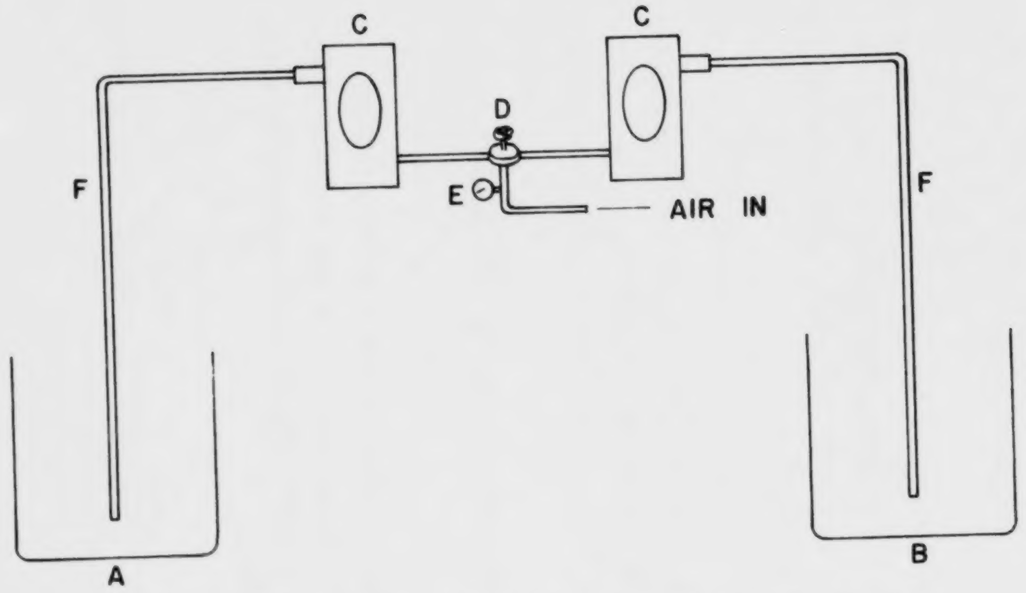
Water Supply

Tap Water --

An approved drinking water source that has no surface active chemical interference present shall be provided.

Wastewater --

Settled supernatant from the activated sludge mixed liquor shall be obtained or, if this is not available, settled composited raw wastewater is



A DISTILLED WATER TANK (PLASTIC), 35-GALLON CAPACITY
B TEST WATER TANK (PLASTIC), 35-GALLON CAPACITY
C DUPLICATE FLOW METERS
D PRESSURE REGULATOR
E PRESSURE GUAGE
F PLASTIC TUBING

Figure C-1. Schematic of alpha test apparatus.

the second choice.

Reaeration Test Water --

The reaeration test water shall be a representative sample of the fluid to be aerated.

Chemicals

Cobalt Chloride Hexahydrate --

Technical grade or better $CoCl_2 \cdot 6H_2O$ shall be provided. Prepare the stock solution by adding 15.2 g of $CoCl_2 \cdot 6H_2O$ to 1 ℓ of water. The addition of a 12.5-ml aliquot of this solution to 25 gal of test water will yield a cobalt ion concentration of 0.5 mg/ℓ.

Sodium Sulfite --

Technical grade, cobalt free, or better Na_2SO_3 shall be provided. Prepare the stock solution by dissolving 200 g of Na_2SO_3 in 1 ℓ of water. The amount of sodium sulfite solution required is calculated as follows:

$$\text{ml of solution required} = (4.65)(C_\infty^*)\left(\frac{100 + \%\ EX}{100}\right) \tag{C1}$$

where:

C_∞^* = DO saturation concentration in the test tank in mg/ℓ

% EX = excess amount of chemical (above the stoichiometric requirement) to be used. % EX ranges from 10 to 25 percent, depending on testing requirements.

Sulfuric Acid --

Technical grade or better H_2SO_4 shall be provided. Add as required to neutralize the water in each tank.

Sodium Hydroxide --

Technical grade or better NaOH shall be provided. Add as required to neutralize the water in each tank.

Reagents for Azide Modified Winkler Analysis --

Use premeasured reagents, such as sold by Hach Chemical Company.

DATA MEASUREMENTS AND RECORDING

Probe Calibration and Interference Determination

Probes shall be calibrated against the results of the Azide Modified Winkler procedure before the start of each test. Three water samples shall be taken from the aeration tanks after the oxygen saturation concentration has been reached. Only pH adjustment chemicals shall have been added to the test water up to this point. The DO probes shall be adjusted as necessary to within ± 0.1 mg/ℓ of the average Winkler value.

Cobalt chloride interference shall be determined by a "blank correction" for each Winkler test. The "blank correction" sample shall be titrated using the standard Winkler procedure except manganous sulfate shall not be added to the sample. Any apparent DO titrated is the interference caused by cobalt oxide reacting with iodide to form iodine. The "blank correction" shall be subtracted from all DO measurements made during the test.

Cobalt chloride shall then be added to the test water and mixed. A second set of three samples shall be taken and Winkler DO analyses performed. If any cobalt chloride interference is present in the Winkler procedure, it shall be noted at this time.

At the end of each test, a set of three additional samples shall be taken and Winkler DO analyses performed. Test results shall then be compared with probe values for verification of the terminal saturation concentration.

In the event that DO probes are not used, samples shall be taken from each tank and analyzed for DO concentration by the Azide Modified Winkler procedure.

Sample Location and Procedure

The sample location shall be at the mid-depth of the test tank, half way between the aeration device and tank side wall. DO probes shall be placed at this location, and sample tubes for Winkler analysis shall also be placed at this location.

Samples for Winkler analysis shall be siphoned into the bottom of a 300-ml BOD bottle. Sample water flow to the BOD bottle shall continue until the BOD bottle has overflowed at least twice to ensure that oxygenation of the sample has not occurred during the filling of the BOD bottle.

DO Measurements

DO shall be measured and recorded continuously throughout the test if a recorder is available. The test recorder strip chart shall serve as the raw experimental data base from which K_La and C^*_∞ are determined.

If samples are taken for Winkler analysis or for remote DO probe reading, the sampling frequency shall be not greater than 5 min between collections per tank. The following sampling sequence is suggested:

Sample Point Number	Tap Water Time (min)	Waste or Test Water Time (min)
1	5	6
2	10	11
3	15	16
4	20	21
5	25	26
6	30	31
7	35	36
8	40	41
9	45	46
10	50	51
11	55	56
12	60	61
13	65	66
14	70	71

Seventy min should be sufficient time to acquire enough data to determine K_La for each water sample at the end of the test. However, the test tap water should be approximately 95 percent saturated. If this does not occur within 70 min, sampling should be continued until this saturation level is achieved. The testing shall then be continued until saturation of the tap water has occurred, at which time samples shall be taken from each tank for the beta factor determination.

Air Flow Measurements

The air flow rate shall be noted and recorded at the start of the test, after every 10 min,and at the end of the test.

The degree of mixing and aeration in the tap water test tank should be adjusted so that the test will yield essentially the same K_La as in the full-scale design at standard test conditions. Use of the same K_La values gives the same degree of tank turbulence for aeration in both the laboratory unit and in the design unit. Under these conditions, the alpha value will be close to that in the design unit.

A number of aeration tests with varying air flow should be conducted on the tap water sample to determine the relationship between air flow rate and K_La. Once this relationship is established, the proper air flow can be selected that will duplicate K_La in the tap water laboratory test and K_La in the full-scale design. The alpha and beta tests shall be conducted at this predetermined air flow rate.

TESTING SEQUENCE

Neutralize biological activity of the wastewater sample by autoclaving or disinfection. Filter the wastewater sample if necessary.

Fill each tank with 25 gal of sample. Keep the temperature constant at the wastewater or test water value. Turn on the air supply, and set the air flow rates equal to a predetermined value for duplicating K_La in the tap water tank and K_La in the full-scale design at standard conditions.

Check the pH of each water sample and adjust to pH 7.0 ± 0.2 as required.

Aerate the samples until saturation has been reached; C^*_∞ should be constant ($\pm$ 0.1 mg/ℓ) for at least 15 min when DO probes are used. When DO probes are not used, the samples should be aerated to the handbook saturation value, adjusted for temperature and pressure at test conditions.

Take samples for Winkler analysis, DO probe calibration, and "blank correction".

Add cobalt chloride to the test tanks and mix thoroughly.

Take samples for Winkler analysis and "blank correction".

Calculate the amount of sodium sulfite required, based on percent excess solution to be used and C^*_∞.

Check the air flow rate to each tank and adjust if necessary; take air flow readings for the beginning of the test.

Simultaneously add the sodium sulfite solution to each tank.

Take samples in accordance with the previously defined technique.

Continue sampling for at least 70 min or until 95 percent saturation has been achieved in the tap water tank.

Continue aeration until saturation has again been reached in the test tanks, take samples for beta factor determinations, and check and record the air flow rate to each tank.

EVALUATION OF TEST DATA

Determination of the Alpha Factor

Alpha is the ratio of K_La of the wastewater sample to K_La of the tap water sample:

$$\text{alpha} = K_La(\text{wastewater})/K_La(\text{tap water}) \tag{C2}$$

Determination of K_La

K_La should be calculated using the method presented in Section 4.

Temperature Correction

K_La at the test temperature, K_La_T, shall be corrected to standard conditions (20°C) by use of the following equation:

$$K_La_{20} = K_La_T/1.024^{(T-20)} \tag{C3}$$

Determination of the Beta Factor

Beta is the ratio of C^*_∞ of the wastewater sample to C^*_∞ of the tap water:

$$\text{beta} = C^*_\infty(\text{wastewater})/C^*_\infty(\text{tap water}) \tag{C4}$$

APPENDIX D

DETERMINATION OF OXYGEN UPTAKE RATES FOR A CONTINUOUS SYSTEM

The rate of oxygen uptake of a continuously-fed mixed liquor begins changing as soon as the sample is removed from the aeration basin for testing. For this reason, the oxygen uptake rate must be determined as quickly as possible. The testing should be performed as near the aeration basin as feasible to avoid time delays. The required steps for the determination are given below:

1. Remove a sample of mixed liquor from the aeration basin. Note the time the sample was taken as time zero.
2. Quickly aerate the sample by shaking vigorously or bubbling air or oxygen through the sample. If the initial DO level of the sample is sufficient (4 to 6 mg/ℓ), perform the test on the sample so as to avoid reaeration of the sample.
3. Place the sample in a flask or BOD bottle. Immediately begin monitoring the decline in DO at regular time increments, 0.25 to 1.0 min intervals, depending on the oxygen uptake rate of the sample. The time data must be related to the zero time noted earlier.
4. When the oxygen content of the sample approaches 1 mg/ℓ, discontinue DO monitoring and quickly reaerate the sample as before. Resume monitoring the decline in DO with time, continuing the time notations from time zero. Measure the sample temperature at the beginning and end of each test.
5. Repeat Step 4 until the endogenous respiration rate has been established, i.e., when the rate remains relatively constant for successive determinations. Repeat Steps 1 through 5 at least twice to enhance the validity of the data. Replicate tests should be performed on samples taken from the same point in the aeration volume.

6. Calculate the oxygen uptake rate for each set of oxygen readings and plot them against time on semi-logarithmic graph paper as shown in Figure D-1. The linear portion of the curve, representing oxygen uptake as a result of endogenous respiration, is extended to time zero. The value of oxygen uptake at time zero represents the endogenous respiration rate of the mixed liquor in the aeration basin. In the example indicated in Figure D-1, this value is 33 mg/ℓ/hr.

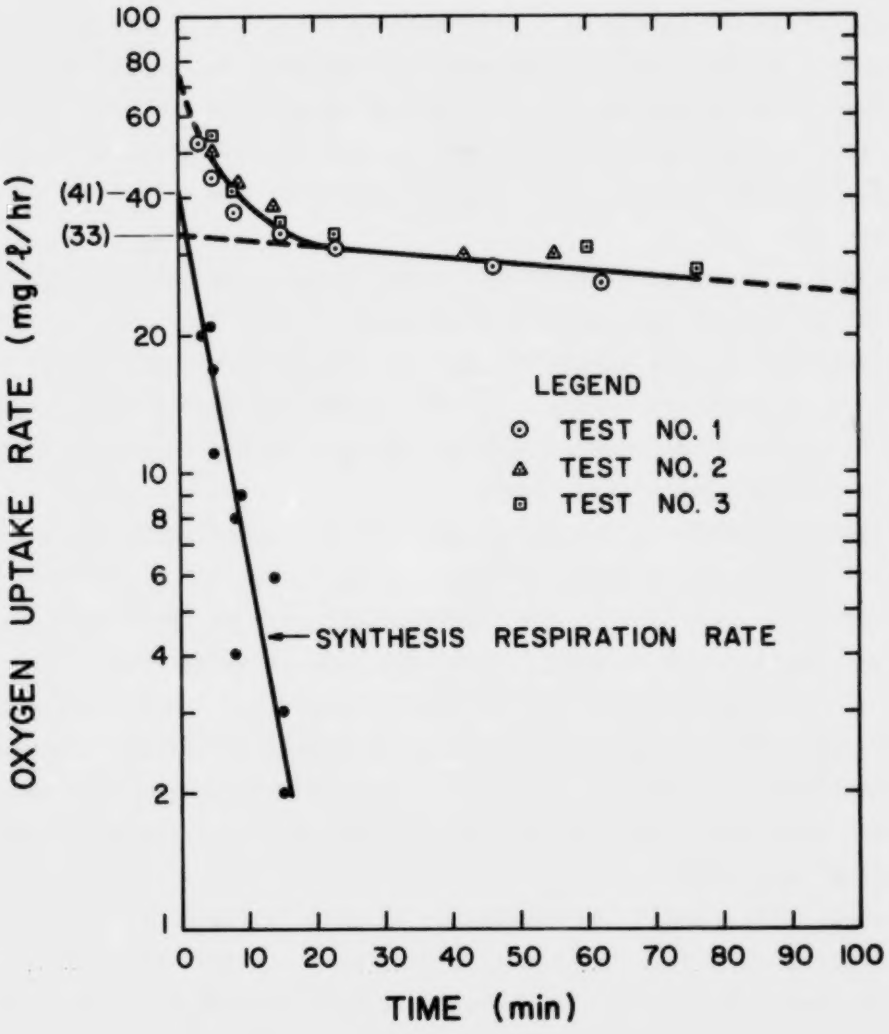


Figure D-1. Estimation of oxygen uptake rate.

7. Subtract the oxygen uptake due to endogenous respiration from the data points on the curved portion of the plot, and plot these differences against their respective time values as indicated in Figure D-1. This line represents oxygen uptake resulting from synthesis. Extension of the line to time zero results in the synthesis oxygen uptake of the mixed liquor in the aeration basin. In the example of Figure D-1, this value is 41 mg/ℓ/hr.
8. Add the endogenous respiration and synthesis oxygen uptake values together to determine the total oxygen uptake rate of the mixed liquor in the aeration basin. In the example of Figure D-1, this value is 74 mg/ℓ/hr.
9. If the average temperature of the sample during testing is different from that of the mixed liquor in the aeration basin, the resulting value for R should be corrected to the mixed liquor temperature by $1.072^{(T-20)}$.

Note that the synthesis respiration rate at time zero, determined according to Step 7, is double the highest value determined by subtracting the endogenous uptake rate from the total oxygen uptake rate (t = 3 min). The possible errors in such a procedure necessitate that the results be considered no more than an estimate of the actual oxygen uptake rate in the aeration basin.

APPENDIX E

BATCH DESORPTION TESTING — PEROXIDE ADDITION DETAILS

DIFFUSED AERATION

Peroxide should be added simultaneously at points along the tank at a distance about equal to the tank width, but with not less than one addition point for each 250 to 300 ft^2 of tank surface (Figure E-1). The release points should be at mid-depth for spiral flow aeration systems and close to the bottom for systems where the aerators are evenly distributed over the tank bottom.

SURFACE AERATION AND TURBINE AERATION (FIGURE E-2)

Peroxide should be injected simultaneously at points located half the distance between the wall and aerator and between aerators (Figure E-2). At least one injection point for each 250 to 300 ft^2 of tank surface is recommended.

BRUSH AERATORS

Measure the flow velocity and calculate the flow time from one rotor to the next. The period of peroxide injection should approximate the flow time. The peroxide should be injected close to the bottom and at mid-width of the tank (Figure E-3).

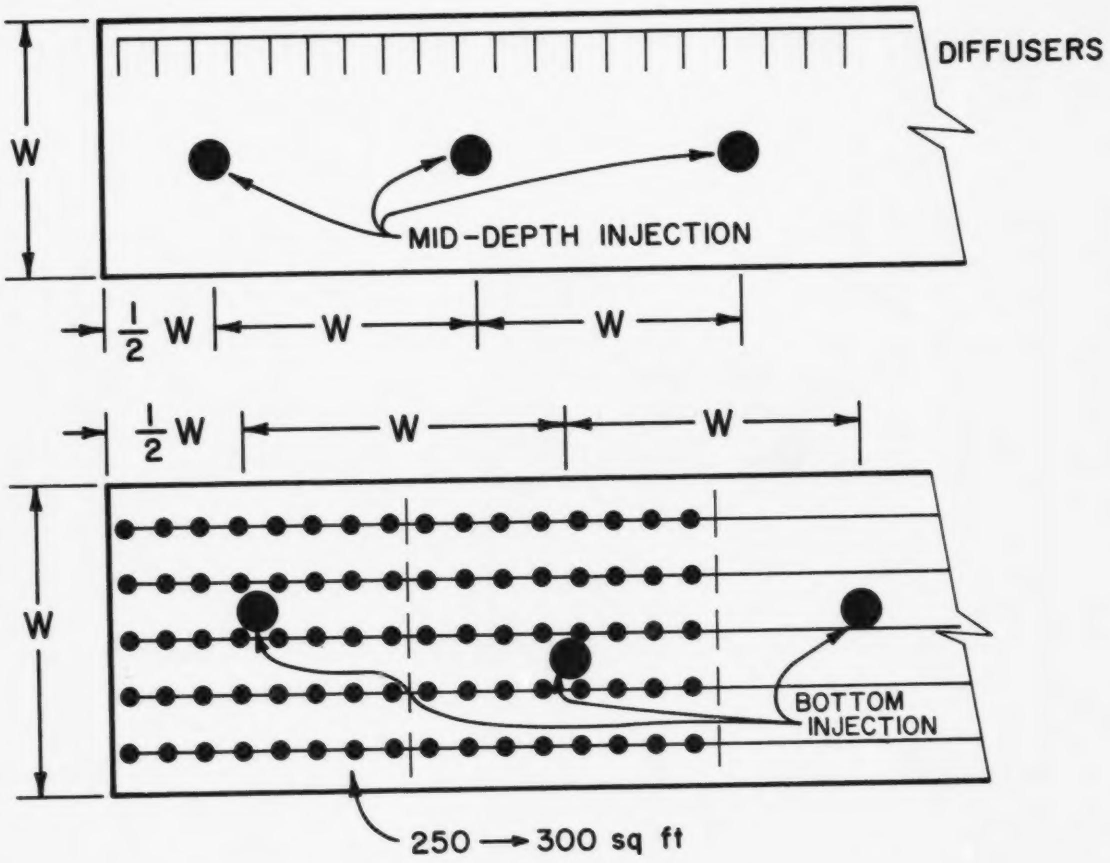

DIFFUSERS
W
MID-DEPTH INJECTION
½ W
W
W
½ W
W
W
W
BOTTOM INJECTION
250 → 300 sq ft

Figure E-1. Diffused aeration — peroxide addition locations.

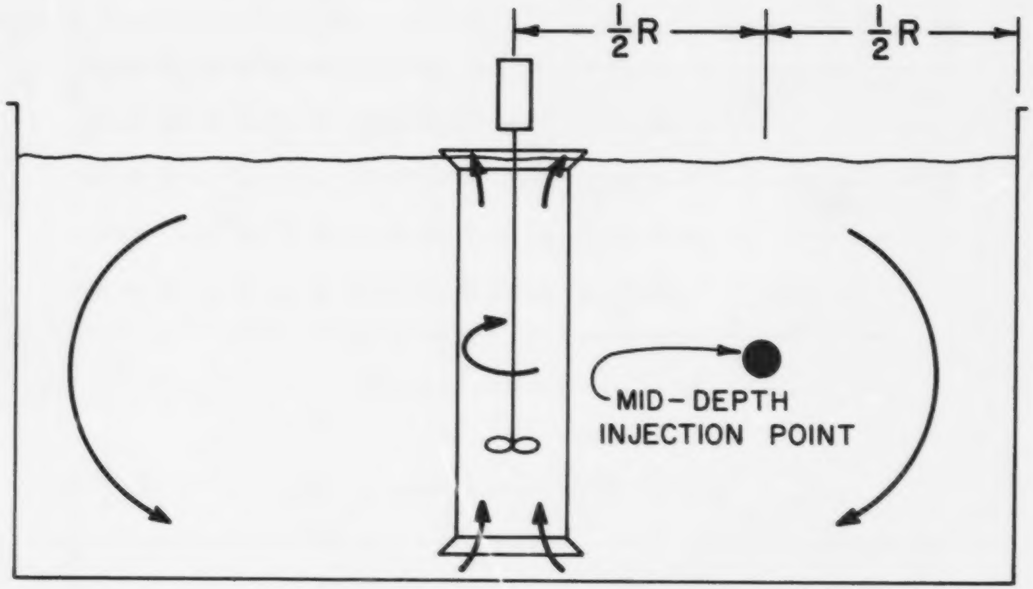
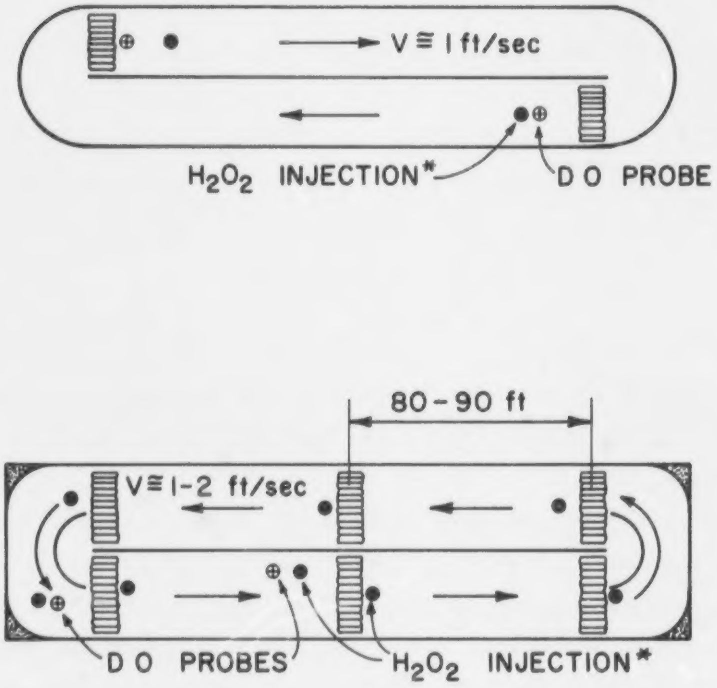

$\frac{1}{2}R$
$\frac{1}{2}R$
MID-DEPTH
INJECTION POINT

Figure E-2. Surface or turbine aeration — peroxide addition locations.


V ≅ 1 ft/sec
H_2O_2 INJECTION*
D O PROBE
80 - 90 ft
V ≅ 1-2 ft/sec
D O PROBES
H_2O_2 INJECTION*

*NOTE: SLOW BOTTOM INJECTION UNTIL DO PROBE SHOWS INCREASE

Figure E-3. Brush aerators in extended aeration oxidation ditches — peroxide addition locations.

APPENDIX F

INDIVIDUAL SAMPLE POINT ANALYSIS

The clean water reaeration test can be used to evaluate DO dispersion. Data from each point are analyzed to evaluate the local uptake rate. Using the equation:

$$\frac{dC}{dt} = K_L a \ (C^*_\infty - C) \tag{F1}$$

a nonlinear curve fit is used to estimate the values for $K_L a$ and C^*_∞. The values are corrected to standard conditions and are identified as $K_L a_{20}$ and $C^*_{\infty 20}$. The procedures for this analysis are detailed in Section 4. The product of these terms is the uptake at zero DO.

To demonstrate the evaluation procedure, test results for three aeration systems are presented (Tables F-1, F-2 and F-3). Each test includes three replicate runs with six sample points. These tables also illustrate the types of limits associated with data reproducibility for the reaeration test.

For the high uptake system, samples were collected every minute during the initial period. For some tests, this time is reduced to 45 or 30 sec. Thus, a split-second delay in sample reading causes measurable variation. The coefficient of variation, CV, for all the data was 9.4 percent. Discarding the three highest and three lowest values (one-third the data) changed the mean uptake rate by only 0.3 percent. CV, however, was reduced by one-third to 6.2 percent.

The standard uptake system (Table F-2) produced the most consistent data. The sample times were spaced 3 min apart. A slight error in timing the sample is not as critical as with the high uptake system. Using all the data, CV was only 5.4 percent. Excluding the three highest and three lowest values reduced CV to 3.4 percent. Once again, there was no significant change in the mean uptake rate.

TABLE F-1. HIGH UPTAKE SYSTEM

Run	dC/dt at zero DO in mg/ℓ/hr for Indicated Sample Points A	B	C	D	E	F
1	90.0	82.8	85.3	80.7	83.5	77.1
2	81.4	96.1	100.1	104.2	100.8	85.7
3	74.7	87.5	86.8	92.3	96.5	96.3

Considering all data points: Avg. dC/dt = 89.0 ± 8.5 mg/ℓ/hr
CV = 9.4 percent

Discarding three highest and
three lowest data points: Avg. dC/dt = 88.7 ± 5.5 mg/ℓ/hr
CV = 6.2 percent

TABLE F-2. STANDARD UPTAKE SYSTEM

Run	dC/dt at zero DO in mg/ℓ/hr for Indicated Sample Points A	B	C	D	E	F
1	38.0	37.3	38.7	39.7	39.1	42.3
2	38.5	40.6	41.2	44.7	43.0	43.8
3	39.9	39.1	41.2	41.0	44.5	42.0

Considering all data points: Avg. dC/dt = 40.8 ± 2.2 mg/ℓ/hr
CV = 5.4 percent

Discarding three highest and
three lowest data points: Avg. dC/dt = 40.7 ± 1.4 mg/ℓ/hr
CV = 3.4 percent

TABLE F-3. LOW UPTAKE SYSTEM

Run	dC/dt at zero DO in mg/ℓ/hr for Indicated Sample Points A	B	C	D	E	F
1	7.4	8.4	6.3	7.4	6.8	8.1
2	6.5	7.4	6.9	5.8	7.2	6.5
3	7.0	6.2	6.5	8.3	6.2	6.9

Considering all data points: Avg. dC/dt = 7.0 ± 0.7 mg/ℓ/hr
CV = 10 percent

Discarding three highest and
three lowest data points: Avg. dC/dt = 6.9 ± 0.4 mg/ℓ/hr
CV = 6 percent

The low uptake system (Table F-3) exhibited the impact of data precision. The uptake in mg/ℓ/hr has only one significant digit to the right of the decimal point. Hence, scatter is introduced by the limits of the ability to distinguish the numerical value for the uptake rate. For extremely low uptake rates, this factor would control data variation. For the test reported in Table F-3, CV was 10 percent. Elimination of the three highest and three lowest values reduced CV to 6 percent.

Using these analysis procedures, all of the tests demonstrated adequate mixing. No single uptake rate value was consistently higher or lower than the mean value. The observed variations, point to point and run to run, were within the prescribed limits.

DO gradients are not a good indicator of mixing. For the reaeration test, DO gradients are directly proportional to the uptake rate and inversely proportional to the aerator pumping rate. For the example of Table F-1 (high uptake system), the gradients at the start of the test were quite severe. As an example, the gradients between sample points B and F were typically 1.0 to 1.5 mg/ℓ. Yet for the three tests, the average uptake rates at these points were within 3 percent of one another. The gradients were progressively less severe for the lower uptake systems.

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